United States Air Force
Scientific Advisory Board

Report on

Alternative Sources of Energy for U.S. Air Force Bases

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Foreword

The Air Force faces substantial energy challenges as it now depends on fossil fuels for a significant part of its energy. The costs and environmental concerns about fossil fuels have risen, as have concerns about mission impacts stemming from energy supply disruptions.

In response to energy-related Executive Orders, federal mandates, and federal and state incentives, Air Force installations are adding alternative energy systems and aggressively improving energy conservation; these commendable efforts, however, are not guided by a concerted systems approach to the problem. This Report provides detailed recommendations that will best position the Air Force to meet its energy challenges.

The Air Force Scientific Advisory Board (SAB) was tasked to study current and projected installation energy needs and potential vulnerabilities, to identify alternative energy sources—including benefits and challenges of each—and to recommend potential near-, mid-, and far-term solutions. This Report presents the findings and recommendations of the Study Panel.

The Study Panel represented a diverse background, including members from Academia, Industry, and Government. Over a six month period, beginning in January 2009, the Panel received extensive briefings, made fact-finding visits, and reviewed technical reports on alternative energy technologies, vulnerabilities, regulatory drivers, current and past projects, and Air Force energy needs. Sources included the Air Force Research Laboratory, industry, academia, National Laboratories, and other government installations. The Panel reviewed past studies and technical papers from the Department of Energy, the Air Force SAB, the Defense Science Board, and others.

The undersigned acknowledge the outstanding efforts by the members of the Study Panel, by the Executive Officers who participated in the Study, by those who hosted and briefed the Panel, and by the Air Force SAB Secretariat in supporting the Study.

Professor Michael J. Sailor	Doctor Joan B. Woodard
Alternative Base Energy Study Chair	Alternative Base Energy Study Co-Chair

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Executive Summary

This Air Force Scientific Advisory Board (SAB) Study was chartered to analyze Air Force installation energy needs and to provide recommendations for solutions, including exploration of alternative energy technologies and systems that will allow the Air Force to meet several energy challenges:

- Reduce energy costs and consumption
- Mitigate operational risks of power loss due to disruptions
- Minimize dependence on fossil fuel sources of energy

In the course of this six month Study, the Panel received briefings and visited organizations involved with the development, installation, use, and maintenance of energy systems. The Panel received briefings from industry groups conducting research and development relevant to alternative energy systems and heard from Air Force and other federal agencies urgently pursuing alternative energy options. The Federally Funded Research and Development Centers provided key briefings and experience in solar, wind, and nuclear energy, as well as in microgrid integration.

Recommendations

The experiences of industry and government organizations were critical to the Panel's understanding of the challenges and opportunities of alternative energy systems and how they relate to the Air Force's energy security picture. The Panel distilled its findings into four top-level recommendations:

Recommendation 1

Implement a more concerted systems approach to the Air Force's pursuit of alternative energy sources. The Panel recommends strengthening in-house competency in areas such as energy technologies, systems security, and energy compatibility with base missions. This is an important step for strategy development and, along with a systems approach, will make the Air Force a "smart buyer" in specific arrangements with commercial partners.

Furthermore, the people within the Air Force civil engineering organizations who focus on energy and security of facilities should be augmented by partnerships with the relevant Department of Energy experts. The Study recommends elevating the role of the Base Energy Manager to strengthen operational understandings of energy security and enable implementation of an enterprise approach to alternative energy systems. By building and expanding competency in these areas, a service-wide "best-practices" approach may be implemented and public-private partnerships developed to reduce the Air Force's cost of implementing alternative energy projects. Additional benefits include strengthened energy security and reduced occurrence of unanticipated costs of energy projects.

Recommendation 2

Strengthen plans for the security of energy sources and distribution elements at Air Force bases. Existing and future energy systems must be hardened against physical and cyber attacks. Planning should include standardized assessments of vulnerabilities and risks and risk mitigation planning for mission-critical priorities. Microgrid and smart grid technologies should be considered, as well as ways to diversify energy sources and supply chains. Bases should work to ensure the capability to run backup generators on jet fuels, and to expand and harden fuel storage facilities. Energy disruptions should be part of training exercises to ensure each base's ability to maintain operations.

Recommendation 3

Pursue energy storage solutions and renewable energy sources concurrently. Alternative energy sources like wind and solar are intermittent; bases need energy storage systems to match energy supply with demand. Energy storage must, therefore, be considered in energy system planning.

In the near-term, the Study recommends storage be incorporated into energy systems for load-leveling and bridging intermittent supplies. Microgrid control systems should also be used to better integrate energy storage to match demand for power and to address the need for improved security and allow independent operation from the commercial grid during disruptions.

For the mid- to far-term, the Study recommends the Air Force partner with others in the development of technologies to create liquid fuels from renewable sources. Liquid fuels are an efficient energy storage medium and are also crucial for aviation operations.

The Air Force should also partner with others on the adoption of clean and efficient backup power systems useful for load-leveling and for the development of hydrocarbon fuel cells or microturbine systems for cleaner conversion of liquid fuels to backup power. The Air Force should monitor and incorporate relevant advances in electric storage (e.g., battery, supercapacitor) and thermal media storage into its energy system plans.

Recommendation 4

Evaluate emerging small nuclear power systems, identify bases that would derive the most benefit from such systems, and make nuclear energy a part of the Air Force's energy planning for the future. The use of small nuclear power plants (those generating 100 megawatts electricity output) could meet an installation's needs and, in addition, supply power to the commercial energy grid from the relatively secure local military base. The Air Force should identify bases that would derive the greatest benefit from nuclear power implementation, perform technical evaluations of nuclear power systems currently in development, and engage industry, other federal agencies, and the other services toward a concept demonstration. These steps will provide the foundation for decisions on a making nuclear energy part of the Air Force's energy future.

Report Structure

The energy challenges facing the Air Force are complex and require a sustained effort to ensure the best solutions support the warfighter and base infrastructure. Through continuous systems planning and analysis, building energy and security competency in the engineering

workforce, and judicious research and development in a few critical areas the Air Force can meet the challenges and capitalize on alternative energy opportunities.

Chapter 1 of this report is structured to present a complete overview of the Study, expanding on this executive summary to provide discussion of the previously released oral presentation material. As such, it provides a record of the content of oral briefings of the Study results and should be used in conjunction with the released briefing material in understanding the perspectives of the Study Panel.

Subsequent chapters provide more detailed discussions of the Panel's findings and recommendations. Chapter 2 addresses the adoption of a systems approach to alternative energy projects. Chapter 3 outlines the need for strengthened security of energy sources and distribution elements. Chapter 4 provides short discussions on the most promising alternative energy sources and outlines the Study's findings with regard to energy storage solutions. Chapter 5 answers the question why the Air Force should consider nuclear energy as an alternative power source for some bases. The appendices provide background and greater detail on all the alternative energy sources the Panel studied (Appendix A), a review of where the Air Force stands in meeting energy-related mandates (Appendix E), and a summary of previous energy-related studies (Appendix F).

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Chapter 1: Introduction

The Air Force Scientific Advisory Board (SAB) was directed to conduct a Study on Alternative Sources of Energy for US Air Force Bases. Alternative Base Energy (ABE) is recognized as an important operational topic with growing interest across the military services. This interest is driven by Executive Orders, federal mandates, increasing costs and environmental considerations. At the time of this Report, every $10 increase in the price of a barrel of oil translates to an additional $500 million annual energy bill for the Air Force.

This SAB Study sought to identify alternative energy options, along with their benefits and challenges, and to recommend potential energy technologies and systems which meet the needs of the Air Force including the ability for the base to operate independently of local power grids. The Study formally began in January 2009 and was completed at the end of June 2009.

This chapter presents an overview of the Study, providing discussion to accompany the previously released oral presentation material.

1.1 The Study's Terms of Reference

This Study was initiated because Air Force installations are heavily reliant on energy supplied from local grids generated from fossil fuels. A 2008 Defense Scientific Board (DSB) study found contingency plans were inadequate even though the Department of Defense relies on the commercial grid for 98% of its installation power.[1] During local grid outages, base operations are interrupted or degraded and the national security consequences of lengthy outages could be significant. The Air Force desires to have alternative energy sources on installations to reduce their reliance on fossil fuels and reduce the impact of power outages.

Many installations are already engaged in alternative energy projects funded by private investors (such as local energy companies) and by the Air Force. These projects tend be initiated by enterprising individuals seizing timely opportunities; they are usually not designed as part of an integrated base energy system.

The complete Terms of Reference (TOR) for the Study are provided in Appendix G of this report. Given the current energy situation, some specific aspects of the Study's TOR proved to be most prominent in our recommendations:

- Analyze energy needs, usage, vulnerabilities, and conservation efforts: the Study found the ongoing conversation efforts to be effective in reducing current usage at Air Force installations. Much progress has been made already, but there are vulnerabilities.
- Identify and assess alternative energy sources and recommend potential technologies and systems for Air Force installations near-, mid- and far-term: the Study found particular attention needs to be focused on power generation and storage solutions.

1 Defense Science Board, 2008.

- Assess the benefits and challenges associated with alternative energy sources: the Study found the Air Force faces significant challenges in operating its bases independently.

1.2 The Study Panel's Composition

The Study Team was comprised of members with diverse backgrounds and experiences, including Academia, industry, and government labs. The list of members and affiliations of each are provided in Appendix H.

Professor Michael Sailor served as the Study Chair, with support from Dr. Joan Woodard as the Vice Chair. The Study Team included eleven SAB members and five consultants. Mr. Michael Aimone (AF/A4/7) served as a Senior Executive Service participant, providing valuable insight and background for the study. Major General Del Eulberg, USAF (AF/A7C) served as the General Officer for the Study. Colonel Michael Rocchetti, USAF (AF/A7CAE) and Mr. Reza Salavani from the Air Force Research Laboratories (AFRL) also provided valuable support to the Study. Dr. Andy Walker of the Department of Energy (DoE) National Renewable Energy Laboratory provided particularly valuable support with analyses using DoE's predictive energy tools. The Team was assisted by Executive Officers and staff from the SAB Secretariat, who provided outstanding technical and logistical support.

1.3 Study Meetings and Briefings

The Panel heard from those involved in the development, installation, use, and maintenance of energy and alternative energy systems. The Panel received briefings from groups associated with seven companies conducting research and development (R&D) relevant to alternative energy systems and from two electric power utility companies serving Air Force bases. Appendix I lists the broad range of organizations that briefed and hosted the Panel during this Study.

In addition to industry, the Panel heard from Air Force civil engineering, research, and operational organizations as well as from other services and federal research centers urgently pursuing alternative energy options.

The Panel made several fact-finding visits to alternative energy projects, including the largest photovoltaic energy system in North America at Nellis Air Force Base (AFB), Nevada, and the "Sunshine to Petrol" project and solar parabolic dish work at Kirtland AFB/Sandia, New Mexico.

Collectively, the inputs from the briefings and visits formed the basis for extensive caucus sessions and analyses by the Study Team, which have led to the findings and recommendations in this Report.

1.4 Motivations for Alternative Energy Projects

A typical Air Force installation has an energy system similar to the one shown in the Figure 1-1, with the commercial power grid providing the bulk of installation's power; mission-critical buildings having backup diesel generators or short-term battery backups; and large liquid energy storage facilities for operational energy sources (e.g., jet fuel for the base's aircraft) that in most cases rely on commercial power for operation.

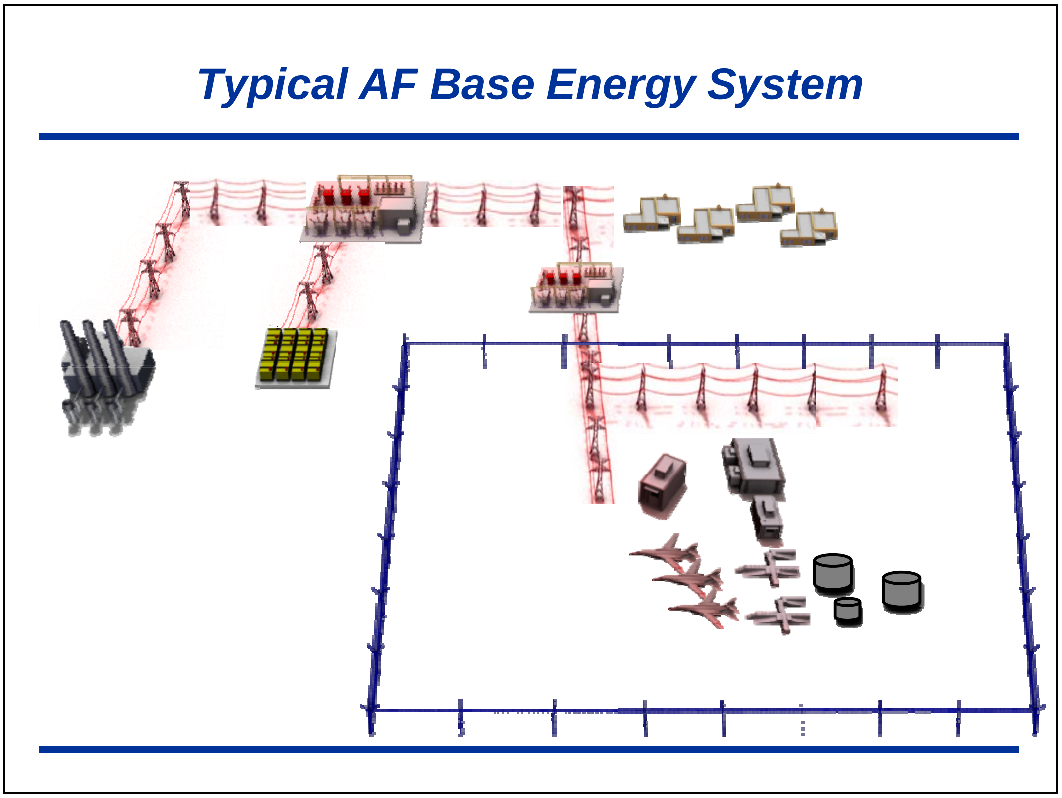

Figure 1-1. Energy Systems of Typical Air Force Bases.

The Air Force does have an array of alternative energy projects underway or in the planning stages at many installations. In each case these alternative energy projects provide renewable energy to help meet Air Force energy needs and policy mandates. However, it is clear not all alternative energy projects provide increased security for the Air Force bases. Such projects are driven by several important external influences, discussed later in this chapter.

1.4.1 Vulnerability of Energy on Air Force Bases

The typical installation's energy system, as shown in Figure 1-1 is illustrative of the vulnerability problem. The reliance of AF installations on local commercial electric utilities results in vulnerability to disruptions in the local power supply.

Furthermore, some power system nodes are attractive targets because they represent single points of failure for the energy supply to the base. Some example vulnerabilities are local substations built outside the base perimeter, local power distribution lines entering a base at just one place, and gas or liquid fuel pipelines feeding a base through a single point.

Many studies have been conducted in this area (see Appendix F for an overview). The Panel reviewed recent, relevant reports from the Air Force SAB and DSB, as well as articles and technical publications in this area. In particular, the 2008 DSB study and the 2007 Air Force SAB study on fuels were quite clear on the existing vulnerabilities, including physical systems and hardware, fuel storage, and control systems susceptible to cyber attack.

The Air Force's predominant approach to emergency response is backup diesel generators connected to mission-essential buildings and run with limited supplies of on-site

stored fuels. The Air Force can reduce the vulnerabilities of the current systems if the new alternative energy projects are integrated into an overall system engineered to provide secure, reliable power.

1.4.2 Fossil Fuel Costs

Fossil fuels are subject to severe fluctuations of price and availability as they are predominantly imported. The overall cost of energy to the Air Force has increased significantly in the past decade, at least doubling since September 2001. Appendix F provides an overview of other studies that have documented the rising costs of fossil fuel usage and the potential impact of renewable energy sources. The bottom line: the Air Force can no longer afford to operate as it has in the past.

1.4.3 Renewable Energy Mandates

Federal policies and legislation are driving a reduction in reliance on fossil fuel as well as substitutions of lower emissions technology to reduce environmental impacts. These federal laws and Executive orders have led to specific Air Force policies and goals for alternative energy usage. For example, Executive Order 13423 mandates a 30% reduction in energy consumption by 2015.[2] Appendix E provides an overview of the policy mandates related to energy usage. The bottom line: the Air Force has been directed not to operate as it has in the past.

1.4.4 Renewable Energy Incentives

Federal and state laws also provide economic incentives for renewable energy. These current incentives make renewable energy projects attractive for venture capital investments and appeal to independent power production companies who propose alternative energy projects for Air Force installations. For example, the Nellis AFB photovoltaics project was built with private investment and provides power to the local utility (in addition to the base).

1.5 Overview of Current Alternative Base Energy Projects

A broad array of alternative energy technologies is available in various stages of development and commercialization. Geothermal, wind, solar, small nuclear fission, and biofuels are just some of the promising possibilities. Figure 1-2 provides a snapshot of the vast work on alternative energy systems deployed or in the planning stages across a number of Air Force bases as of July 2008. The projects range in size from the small 170 kilowatt (kW) solar photovoltaic system under development at the Fresno Air National Guard base to the large 14.2 megawatt (MW) solar photovoltaic system already operational at Nellis AFB. These systems are used for a range of applications, from generating electricity for the local electrical grid, to heating hot water, to providing heat for buildings.

2 Executive Order (E.O.) 13423 affects requirements for renewable energy in Federal facilities. The goal specified here is required by EPA Act 2005: 3% by 2009 (achieved 3.4%); 5% by 2012; 7.5% by 2013. The statute allows agencies to double count renewable energy if it is produced on-site and used at a Federal facility, produced on Federal lands and used at a Federal facility, or produced on Native American land and used at a Federal facility. E.O. 13423 requires that at least half of this renewable energy must come from new renewable sources (installed after 1999).

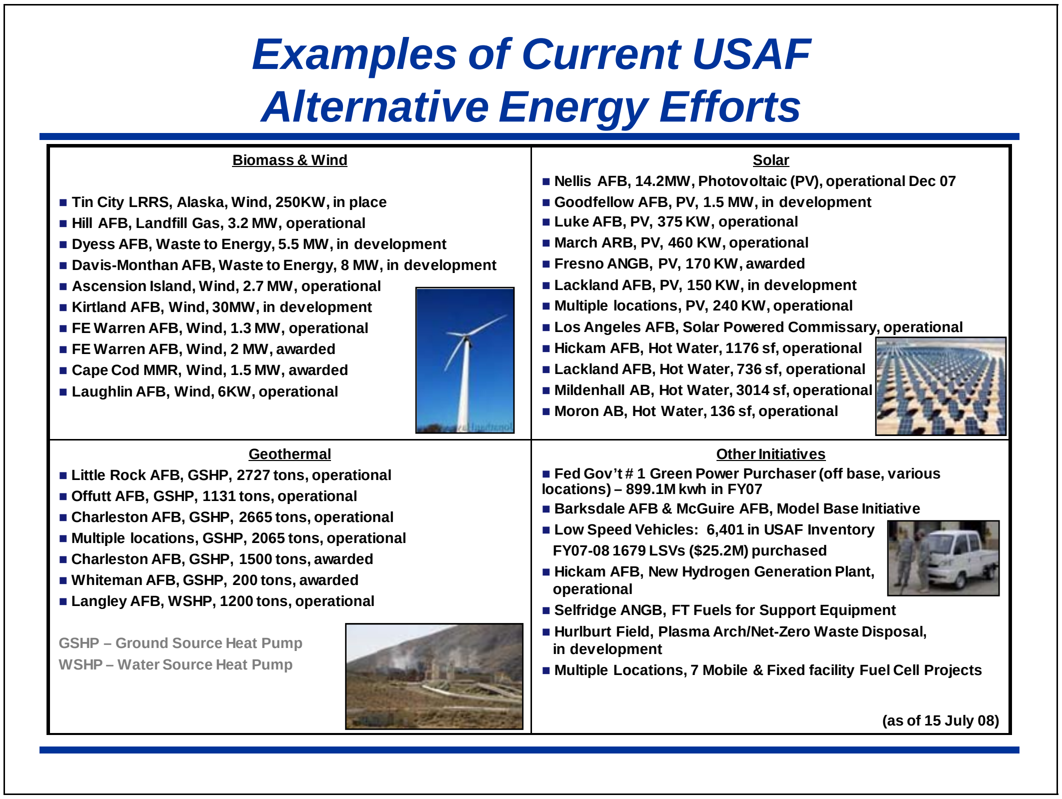

Figure 1-2. Examples of Alternative Energy Projects Across the Air Force.

These projects are in response to the Air Force's Energy Infrastructure Strategic Plan.[3] A central pillar of that plan is to increase renewable energy use for Air Force base needs at specified annual rates. However, the impetus and motivation for these alternative energy developments tends to come from specific, dedicated individuals at the individual bases. These individuals have taken the initiative to investigate a variety of technologies, identify potential funding mechanisms, and pursue partnerships with commercial, state, and other federal organizations to make the projects feasible and to execute them.

As an example, Little Rock AFB began the process of installing geothermal heat pump systems to replace air-source heat pumps for nearly 1,000 homes on base (prior to base housing privatization). The base contracted with a local company to manage the system's design and installation. This was accomplished using an area wide utility contract, which allows any federal agency in the utility's area to sign on to the contract. The contractor provided all the upfront capital for the nearly $10 million project. The project was expected to save the government over $1 million annually.

This is typical of many of the ongoing alternative energy projects which are based on public-private partnerships. Because the Air Force does not put up the initial investment money for the project, it is able to participate in such projects with little near-term fiscal impact.

As will be shown, however, this benefit is not without long-term cost. The Panel recommends the Air Force develop a more systematic approach to alternative energy projects.

3 United States Air Force: Air Force Policy Memorandum 10-1, 2008.

Most base-level activities occur in parallel with execution of the more standard duties assigned to base energy managers. Motivation for these efforts, in some cases, is simply to save the Air Force money by taking advantage of utility incentives, meet federal mandates, or solve environmental problems. The Panel's analysis of 87 bases identified $426 million of investment in renewable energy projects[4] with a projected annual cost savings of $46 million, not including federal, state, and local incentives that may be available.

1.6 On-Base Energy Projects: Challenges and Compromises

As a means of illustrating the challenges and compromises encountered in on-base energy projects, we compare two existing energy generation systems on Air Force bases: Nellis AFB's photovoltaic solar system and Tinker's gas turbine generation system. Table 1-1 summarizes a comparison of some critical aspects of each base's project.

Base	Nellis	Tinker
Project	14 MW solar photovoltaic panels	80 MW natural gas turbine "peaking plant"
Benefits to AF	No net capital cost to AF Annual savings of ~$1M	No net capital cost to AF Upgraded grid Increased reliability
Mandates	Counts towards renewable energy mandates	Does not count towards renewable energy mandates
Operation	Operated by contractor Intermittent supply	Operated by contractor On-demand supply
Grid Outages	No access to power	Provides base power

Table 1-1. Comparison of Two Alternative Base Energy Projects.

Although both of these developments have been beneficial to the Air Force, neither was undertaken with an optimized view across all of the potential alternative energy technologies. Because efforts like these do not stem from any central organization within the Air Force, for the most part they do not reflect a systems-level view. In deciding what alternative energy technologies would be most beneficial at a given location, a variety of factors should be considered:

- Economic factors such as the cost of the energy relative to power from the electric grid
- Security factors such as whether power can be delivered regardless of commercial electrical grid outages
- Physical factors such as the availability and feasibility of local energy production, which is especially relevant for solar, wind, and geothermal methods of power production
- Technological factors such as the maturity of the technology and the ease or difficulty of its manufacture, integration, and operation as part of the local energy grid.

4 Thirty-two bases have projects in the works that will generate 214 MWe using wind power; seven bases are working on solar ventilation air preheating; and twelve bases are implementing solar water heating.

Such calculations are further complicated by the impact of government financial incentives, the availability of resources, and energy policy mandates pressuring base leaders to meet energy targets that may or may not be realistic for the geography and security needs of the base. A more centralized, systems-level engineering approach to such projects would lead to further advances of these commendable pilot-efforts.

1.6.1 Nellis AFB Photovoltaic Solar System

Nellis AFB developed a solar photovoltaic (PV) system that will bring the Air Force significant savings over the project's anticipated life. Completed in December 2007 after 3 years of planning, the project is North America's largest PV power plant. The project comprises an array of more than 70,000 solar panels mounted on more than 6,000 multi-axis and single-axis trackers. The peak power generation capacity of the plant is approximately 14 megawatts electrical (MWe), supplying the base with about 25 percent of the total power used by its population of about 12,000 people.

The PV system is the result of a public-private partnership that includes Nevada power companies and subsidiaries. Under the terms of a Power Purchase Agreement, the company retains ownership of the panels and leases the land at no cost from the government. The Air Force paid none of the $120 million construction cost, which was raised by the energy and venture capital firms from private sources. Nellis AFB agreed to buy the power for 20 years at approximately 2.2 cents per kilowatt hour (kWh) from the company. Compared with the current cost of power in Nevada (about 9 cents per kWh), Nellis will save approximately $1 million each year.

The basic financial model followed in this situation is relatively simple: the PV array produces renewable energy (solar) and earns federal renewable energy credits. Nellis AFB purchases the renewable energy while the power company earns the renewable energy credits to meet the State of Nevada's Renewable Energy Portfolio Standard. The revenue from Nellis AFB is used by the company to operate the facility and to pay the construction and maintenance costs. A key element was an incentive from the State of Nevada of approximately 17 cents per kWh for the renewable energy source. Nellis AFB counts this energy source as part of its mandate to acquire renewable energy.

However, this PV plant is structured only to supplement base power during daylight hours. The plant is wired directly to the local electrical grid and is configured in such a way as to require energy from the grid to operate. Therefore, the PV plant cannot supply any electricity to the base in the event of grid failure. Hence, the development did nothing to enhance the security of Nellis' energy supply.

1.6.2 Tinker AFB Gas Turbine Plant

A different approach was taken by Tinker AFB. At Tinker AFB, leaders focused more on enhancing energy security by attracting the local utility to construct an 80 MWe gas turbine plant on base.

The advantage to the utility company stems from its ability to use the plant to provide off base peaking power during high demand periods. The advantage to the Air Force arises from the plant's assuring the base of instantaneous access to power to meet all critical base needs in the

event of grid failures. Because of this arrangement, the energy security of Tinker was enhanced by the project.

Like the PV array at Nellis AFB, the Tinker AFB plant was accomplished at no net cost to the Air Force. However, the energy source itself has a more substantial carbon footprint than Nellis AFB's PV generation and, therefore, Tinker cannot count this project as helping to meet its renewable energy mandate.

1.7 Building a Notional Alternative Energy System

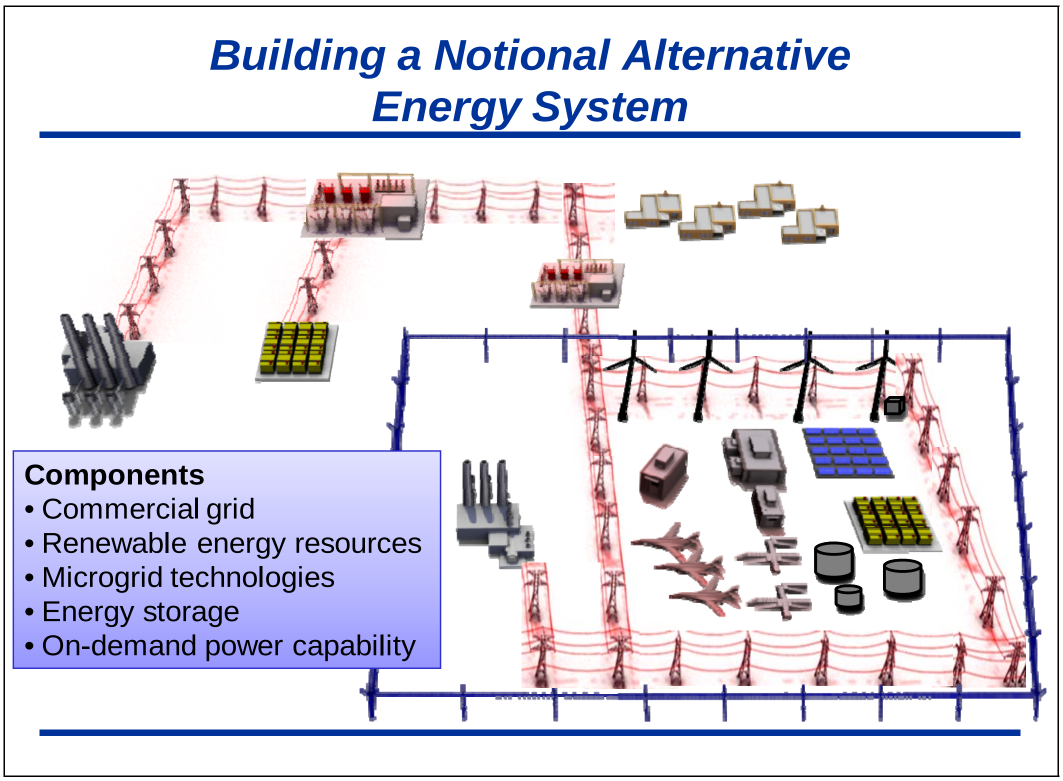

Figure 1-3. Notional Alternative Energy Architecture for a Base.

The Panel's analyses of Air Force bases illustrates that one size does not fit all. The Air Force has an immediate need and immediate interest in secure, renewable energy, but is not currently on track to meet these needs because it has not adopted a systems solution to help address all the important factors. Furthermore, the civilian sector provides a much bigger application for the country's R&D energy investments. The Panel's findings and recommendations all point to the need to tighten our energy focus and strengthen a partnership with the Department of Energy (DoE) as the Air Force moves forward with targeted personnel and R&D technological investments.

Figure 1-3 (above) illustrates an installation's notional alternative energy system. Components of this strengthened, notional system include renewable energy sources; modern microgrid technologies to strengthen the energy architecture and security;[5] sufficient on-site

5 See Vanek & Albright, 2008 and Celli et. al, 2005.

energy storage solutions to prevent operational disruption during commercial grid outages; and on-demand power generation capability for independent operation.

Evaluations of alternative energy systems must be performed in recognition of the relevant directives and guidance and must consider risks, payoffs, and costs in order to drive the Air Force toward the best solutions for its bases. The solution will not be the same for each base, but there will be lessons learned and process developments that might assist other bases in their evaluations. Therefore, the Air Force needs to develop a cadre of energy professionals who are professionally trained to perform alternative energy evaluations, who share their lessons learned, and who can evaluate the data and information developed from other sources and partners.

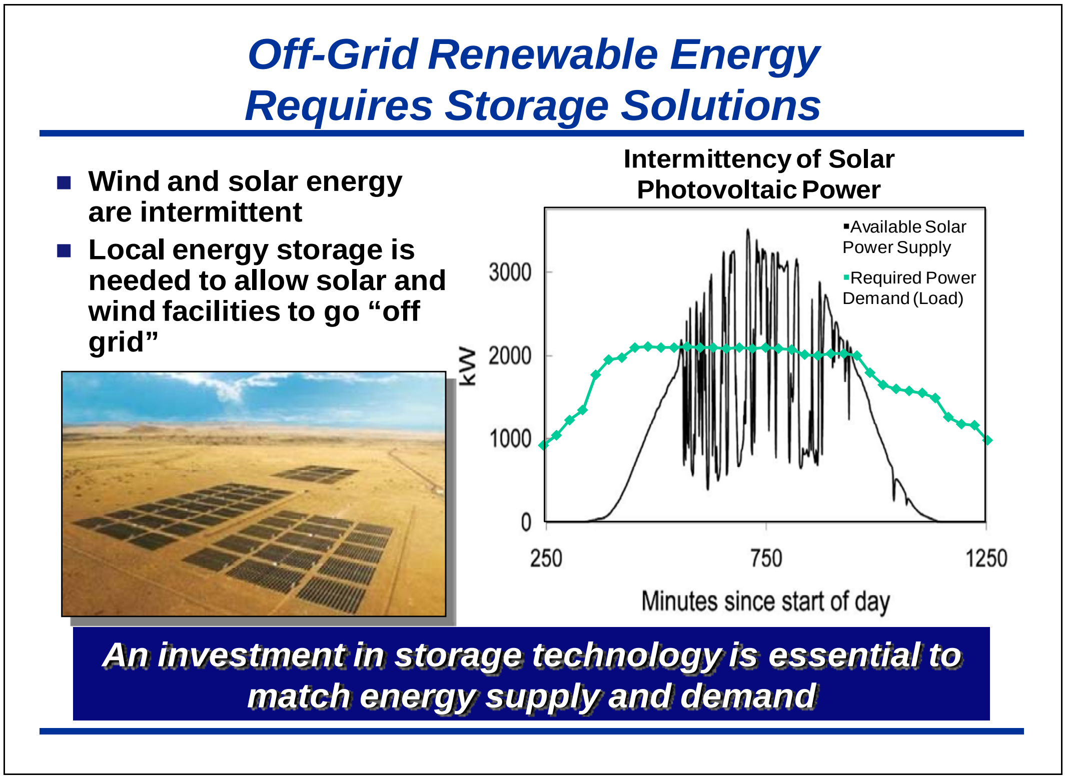

Figure 1-4. Renewable Sources of Energy Require Storage Solutions to Meet Demands During Off-Peak Production Periods.

Natural renewable energy sources tend to produce power intermittently, with output gaps ranging from minutes—as caused by cloud cover over solar PV systems—or hours, as happens to solar systems at night. Therefore, energy storage is necessary for many renewable energy systems. For example, Figure 1-4 (above) compares the typical intermittency of a solar PV system such as the one at Nellis AFB with a typical daily load.[6] Energy storage allows capture of power generated at peak production times for use during low production times. Currently the Air Force mitigates short interruptions with battery back-up systems and longer outages with liquid fuel-fired diesel turbine generators. Since many Air Force bases have an abundance of liquid fuels for aircraft, jet fuel would be an obvious source for power during longer outages and should be integrated into a micro-grid energy concept.

6 United States Electric Advisory Committee, 2008.

The Air Force needs to move toward having a "Secure Energy Grid" for each Air Force base. This would be premised on a microgrid architecture that includes modern power monitoring and automated back-up and shut down capabilities. By providing micro-grid networks that could be isolated from the regional grid in times of accident, attack, or natural disaster, a base could supply its own power needs for a long period of time. For alternative energy sources, the microgrid concept offers the capability to plug in resources, but still allows control of the load sharing between elements of the system in order to maintain the balanced loading necessary to adapt to the high intermittency of renewable energy sources such as wind and solar power. Likewise, it would link the systems to the base energy storage capability to bridge those times when system demand exceeds energy output.

Recent developments of small nuclear reactor designs that offer safety, stability, and reasonable size for power ratings less than 50 MWe are under development and heading toward Nuclear Regulatory Commission (NRC) licensing.[7] The Panel recommends the Air Force evaluate the use of such systems for generating base energy in conjunction with other renewable energy systems. Nuclear fuels offer the highest energy density beyond liquid fuels. If they were used for base energy generation, liquid fuels could be saved for vehicles and aircraft. The evaluation of small nuclear power plants should encompass the same considerations as the other alternative power systems identified in this report. Security, maturity, safety, availability, and economics will drive these evaluations, just as they would the alternative energy system trade-offs. The economic viability of these systems is undetermined, but worth monitoring since these smaller systems will change the landscape as they become economically viable.

1.8 Summary of Findings

The Panel finds Air Force bases at present have vulnerable energy sources, but that new capabilities like micro-grids, smart grids, and on-site alternative power sources could mitigate the risks. Wise selection of the best solution for each base depends, ultimately, on a system-level trade study. Such a study must be performed to determine which alternative power systems can provide the optimal financial, operational, and security solution for each Air Force Base. The specific primary findings of the Panel are summarized as follows:

- Evaluating and implementing alternative energy systems must include consideration of a wide variety of parameters. Expertise for evaluating all the variables and financial and technological exigencies are not sufficient at every base.
- Implementing alternative energy sources requires a system-level approach not yet apparent in the Air Force—this is essential for getting the most out of alternative energy technologies.
- Despite known vulnerabilities, the security of energy sources and distribution elements at bases is lacking: the primary drivers for implementing alternative energy projects do not also drive security enhancements or mitigate the vulnerabilities. The security of energy for the base is not of primary concern to contractors and commercial sector power providers who often implement such projects on Air Force bases.
- Improved energy storage technologies are needed as storage is essential for maximizing the use of power from renewable energy systems and to better manage a

7 Ingersoll, 2009 and International Atomic Energy Agency, 2005.

base's energy load. Bases need the capability to conduct their missions effectively when cut off from the regional power grid.

- Nuclear energy complements renewable energy—nuclear is a major option for carbon-limited futures and for independent operation. A study by the World Energy Council[8] suggests renewable sources can provide only 20-40% of the estimated growth in power demand over the next 60 years. As shown in Figure 1-5 below, nuclear power is the only major low-carbon option available.

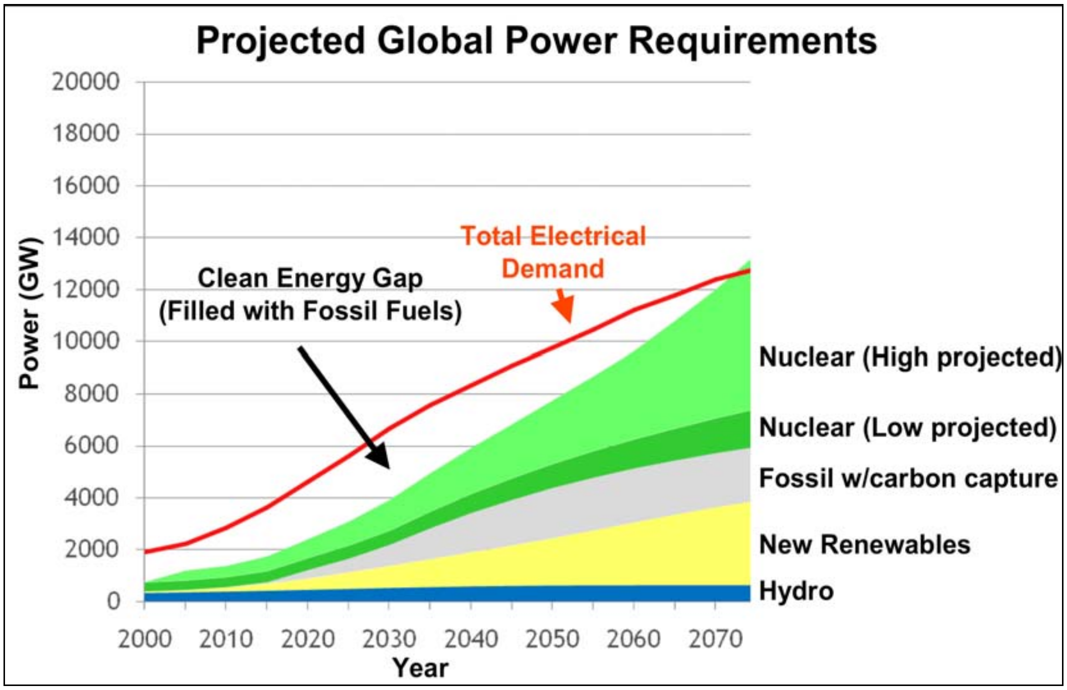

Figure 1-5. Estimated Global Power Requirements. (Note: In a Carbon-Limited Future, Only Nuclear Power Provides an Option for Meeting Power Demands.)

1.9 Summary of Recommendations

This Study presents four recommendations to the Air Force leadership. First, the application of a systematic approach is essential to the successful implementation of alternative energy on Air Force installations. The ability of a base to assess all facets and considerations of alternative energy infrastructure (ultimately leading to a systems plan for that base) will be greatly increased if it has not only the resources (manpower and funding), but also the lessons learned and experience of other Air Force installations, the other military services and other government agencies such as the DoE. A critical piece of the systems approach will be the leveraging of public-private partnerships to make alternative energy implementation economically feasible. None of this is feasibly managed at the local base level.

Next, the Air Force needs to implement its existing guidance on energy security by assessing and prioritizing mission-critical capabilities. Based on the Service-wide assessments, the Air Force should take concrete steps to mitigate the risks to these critical assets through the

8 World Energy Council, 2007.

incorporation of new technologies such as microgrids, diversified energy sources, and hardened energy grid components. Increasing the awareness of warfighters to their energy vulnerabilities and enhancing their ability to "fight through" disruptions needs be evaluated during base exercises. Appropriate investments need to be made to ensure survivability of critical capabilities.

The third recommendation addresses a key limitation of intermittent alternative energy sources such as wind and solar power and also aids in energy security: The Air Force needs to invest in and implement energy storage technologies. In the near-term, several technologies exist that the Air Force could implement to increase the feasibility of the alternative energy sources, for example, switching from diesel backup generators to hydrocarbon-based fuel cells that could use aviation fuel, an abundant energy storage medium already available at many bases. In the mid-term, this storage development should expand to the ability to produce aviation fuels from renewable sources. As the Air Force is heavily dependent on aviation fuel, this capability not only provides an excellent energy storage medium, but also diversifies its supply of needed fuel. The Air Force needs to continue to harvest new technologies that emerge from the public sector in the areas of batteries and thermal storage media while making smart R&D investments in renewable-to-liquid fuel technologies.

Complementary Roles: Renewables and Small Nuclear

		Renewables	Small Nuclear
SECURITY ASPECTS	Vulnerability to attack	Medium	Low
	Consequences of attack	Power Loss	Power Loss / Potential Release
	Availability 24/7/365	Technology dependent	Yes
SYSTEM ASPECTS	Geography independent	No	Yes
	Land footprint	Large	Small
	Maturity	Commercially available	NRC Licensing required*
	Load following	Intermittent	Base Load
	Public perception	Positive	Improving

****US Navy, US Army small reactors mature but not relevant for powering installations***

Figure 1-6. Comparison of Key Aspects of Renewable and Small Nuclear Power Sources.

Finally, the Air Force needs to incorporate nuclear energy into its future energy plans. Small nuclear plants may provide an exceptionally secure, constant supply of electricity, requiring no storage and producing no carbon emissions. As nuclear sources will almost

assuredly be a part of future energy strategies worldwide, the Air Force should evaluate nuclear options for selected installations. Figure 1-6 above compares aspects of renewable energy to small nuclear power sources and shows the complementary roles between intermittent renewable sources and secure, stable nuclear power options.

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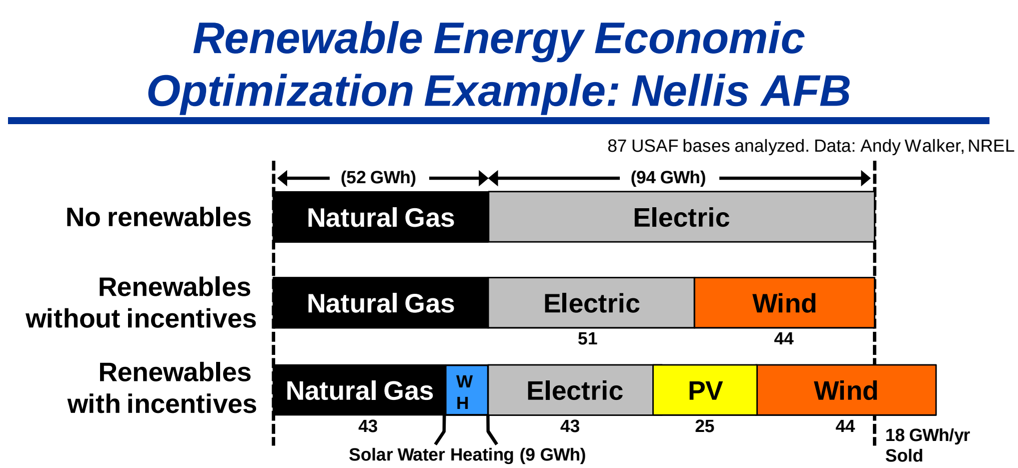
Chapter 2: Enhancing a "Systems Approach" to Energy

The Air Force faces considerable challenges in deciding how best to meet government mandates and integrate alternative energy sources in a cost-effective, environmentally sound manner. The first chapter summarized important considerations for the Air Force as it moves forward on alternative energy projects. This chapter and the next add the additional imperatives of training and security as key components to an overall system engineering and risk management strategy for the Air Force.

2.1 Develop In-House Energy Competency

Most of the individuals and organizations briefing the Panel had a common-sense understanding of the design and operating principles driving energy management and security; however, it was clear to the Panel that no consistent understanding exists and is shared across the Air Force for guidance in making energy decisions.



	Photovoltaic Size (MW)	Wind Size (MW)	Solar Water Heating (MW)	Energy Savings (GWhr/yr)	Energy from Renewables (%)	Total Initial Cost (M$)	Rate of Return (%)	Payback Period (yrs)
Without Incentives	0.0	10.6	0.0	44	30	21	12.5	7.4
With Incentives	14.0	10.8	3.6	78	51	63	6.5	12.6

* Incentives: 30% Federal Tax Credit; accelerated depreciation; $2.4/W rebate; $0.05/kWh production incentive, same incentives as reported for Nellis PV project, incentives for large projects are negotiated individually.

Figure 2-1. The Study Analyzed Some of the Factors for 87 Air Force Bases with Tools Available from the National Renewable Energy Laboratory.

The technical and policy issues associated with developing alternative energy systems requires capabilities in energy monitoring and data analysis, expertise in energy and mission support technologies, and deep engagement with local power suppliers and state officials. These

issues are complex and require detailed knowledge of mandates, incentives, energy costs, and financial models on top of all of the technical issues associated with the technologies themselves.

In-house Air Force energy competency in these areas is essential to increasing the effective use of alternative energy at Air Force bases. For example, Figure 2-1 shows an analysis of the economic optimization of Nellis AFB's PV project using tools available from the National Renewable Energy Laboratory. Without the competency to perform such analyses, the Air Force will not be able to evaluate proposed concepts and systems independently.

The Air Force must develop a cadre of energy professionals who are professionally educated in the relevant issues, who share information across the Service and who can evaluate the data and information developed from other sources. This will help ensure that lessons learned at specific Air Force facilities can be applied across the enterprise as a predicate for a robust systems approach to energy.

2.1.1 Expand the Role of Base Energy Managers

Base Energy Managers are well placed to play a fundamental role in achieving Air Force energy goals. However, limited resources may impact their ability to implement and maintain strategic energy management practices at the base level.

The Base Energy Manager reports to the Asset Management Flight Chief, a new position created under the recently reorganized Civil Engineering Squadrons with a portfolio combining the legacy environmental, housing, real property, and community planning functions. At the GS-12 level, the grade of the Base Energy Manager may be too low to project the level of influence necessary to facilitate base-wide cultural changes. Furthermore, Energy Managers are in high demand in the private sector, making tenure short and resulting in limited continuity for longer term projects and programs.

The Base Energy Manager position requires a wide range of skills and knowledge that must be kept current with emerging technologies. Comprehensive and continuing education programs will be critical contributors to the success of Base Energy Managers. Furthermore, Base Energy Managers need access to modeling tools to guide their planning and operation of base energy systems and to help support the continuity of long-term planning during personnel turnovers.

2.1.2 Establish DoE Liaison Functions

The Department of Energy is the lead federal agency for all energy matters. Included in its mission is the advancement of the energy security of the United States and promotion of energy-related scientific and technological innovation.[9] It collects, analyzes, and distributes energy data. As such, DoE could be a critical resource for understanding Air Force energy issues, for assessing new energy technologies, and for evaluating options in alternative energy and energy security planning. To better utilize this resource and to support Air Force planning, a DoE liaison should be placed at each Major Command to support the Base Energy Managers.

9 United States Department of Energy: About DOE, n.d.

2.1.3 Use the Federal Energy Management Program

The DoE's Federal Energy Management Program (FEMP) offers technical advice, expert analysis, and energy analysis tools to Federal Energy Managers. The FEMP was created to facilitate the Federal Government's implementation of sound, cost-effective energy management and investment practices.[10]

Currently, FEMP provides technical and design assistance to help agencies resolve technical obstacles to project implementation. Federal agencies request assistance through a biennial "Call-for-Projects" and on an ad hoc basis through FEMP representatives in the regional offices. As their website indicates, FEMP does not provide routine engineering assistance, but instead focuses on projects that use a new technology, new application, or non-standard implementation strategy.

The Air Force should task the Air Force Facility Energy Center at the Air Force Civil Engineer Support Agency (AFCESA) to partner with the DoE to expand the FEMP to provide a team of energy professionals that can provide on-call support to Base Energy Managers. The Air Force will need to negotiate a long-term agreement with FEMP to staff and adequately resource this team of alternative energy experts to help Base Energy Managers navigate the complex maze of regulations and alternative energy resources.

As Base Energy Managers work with this dedicated team of FEMP experts, energy security must be an integral part of the planning process. Currently, FEMP uses a competitive ranking process to select projects that demonstrate the greatest value in terms of potential energy savings, replication, public education, and other benefits. In addition to these usual parameters of return on investment, mission criticality must also be included as a factor for the Air Force in energy project funding decisions, a recommendation the Panel addresses further in Chapter 3.

2.2 Pursue Public/Private Partnerships

The Air Force has made substantial investments in developing selected new energy technologies. At the same time, a vast worldwide effort in industry, academia, and government has been underway for decades pursuing a variety of options. Some of these promising efforts are described in Chapter 4 where partnering in strategic cases between the Air Force and private enterprise is recommended. Here the Panel focuses on a different area, namely public/private partnerships to implement renewable energy projects on bases.

Most Air Force installations obtain primary power from non-military providers in the local, state, or regional communities. These providers are combinations of public and private entities that are heavily regulated and present the Air Force with a varied set of incentives, opportunities, and restrictions on obtaining energy for base operations. The Air Force's overarching energy strategy should promote partnerships with power providers (utilities, grid operators, fuel suppliers) in ways that provide mutually beneficial provision and access to secure and reliable energy for bases.

10 United States Department of Energy: Federal Energy Management Program, n.d.

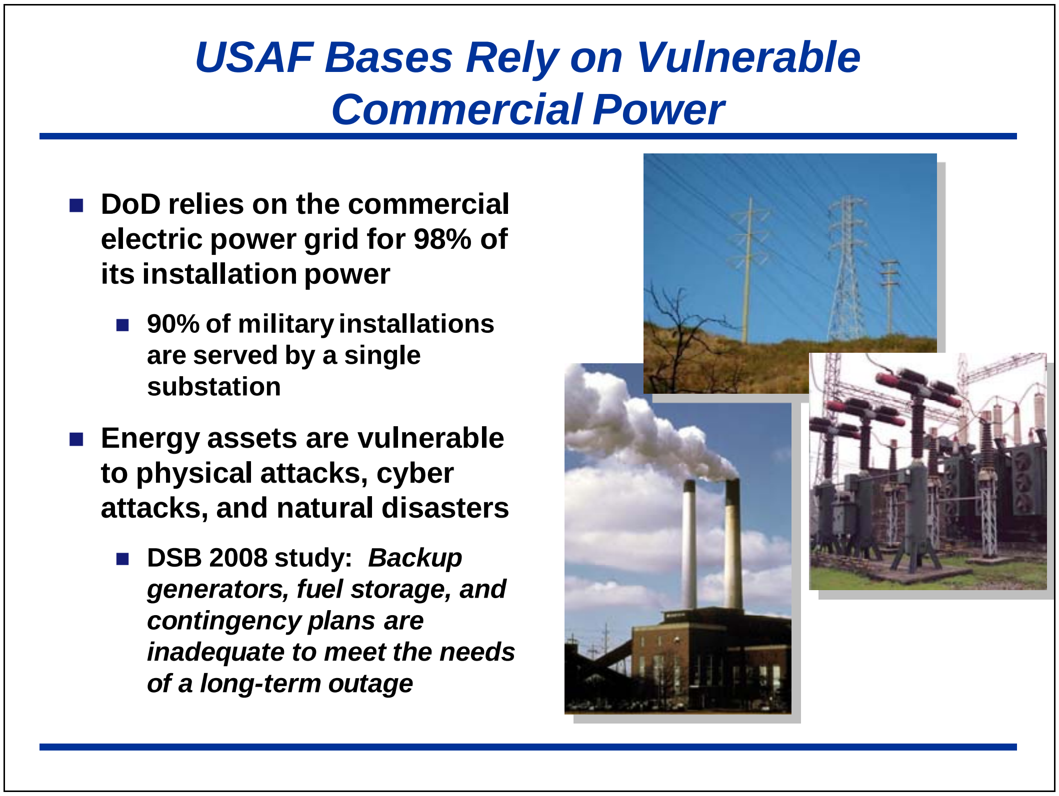


Figure 2-2. A 2008 Defense Science Board (DSB) Study Found 90% of Installations are Served by a Single Electrical Substation.

A number of bases have already engaged in successful partnerships with private industry and public utility providers to install renewable power supplies. An instructive example is the solar PV array at Nellis AFB. The project tasked the developers[11] with the design, financing, construction, and operation of the PV array. For their efforts, the developers entered an agreement to sell the power to Nellis AFB at an agreed price through a Power Purchase Agreement. Nellis AFB provided the land for the array via a land lease.

The useful lesson from this example (and several others at other bases) is that private industry will actively partner with the Air Force to pursue projects if a state has an aggressive structure for renewable portfolio standards, energy credits, tax incentives, and rebates to make a project financially viable. The Air Force can bring project stability via land lease and Renewable Energy Power Purchase Agreements to assist in achieving financial viability for the project. The Panel recommends the Nellis AFB model be used at other bases to develop and, if applicable, operate on-site renewable energy sources.

11 Partners included the local utility (Nevada Power), a contractor for design and development (Sun Power Corporation), and a financing company to own and operate the system (MMA Renewable Ventures).

2.3 *Develop an Enterprise-wide Plan Recognizing Every Base is Different*

Each alternative energy technology has advantages and disadvantages for a specific base, depending on financial, technical, and geographic variables. Air Force installations differ in their energy demands and opportunities. Nellis AFB's solar PV system would not be the appropriate choice for Hanscom AFB in Massachusetts with a different natural and regulatory environment.

In order to best meet its goals, the Air Force needs a system-level plan for each installation to take all the relevant factors into account. For example, Figure 2-3 summarizes an analysis by the National Renewable Energy Laboratory (NREL) of what would be required for Kirtland AFB to operate independently of the commercial grid.

The Air Force needs to perform such in-depth analyses, fully accounting for its energy goals and the relevant factors and constraints of each base. Such an analysis will require bases to partner with local industry and power suppliers. Beginning such partnerships may reveal unrealized opportunities for improvements without significant capital investments by the Air Force.

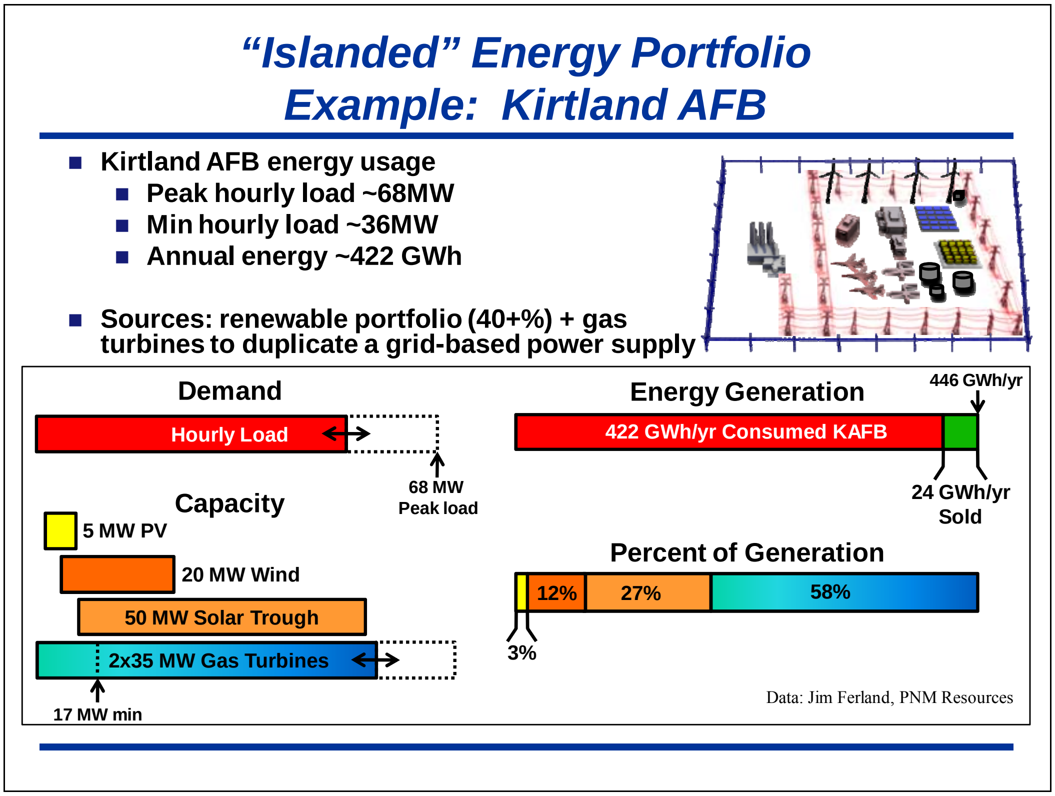


Figure 2-3. An Analysis of Kirtland AFB Provided by the Local Commercial Utility, PNM Resources. (This analysis is not an economic optimization for lowest energy cost, provides for independent operation of the base from the local utility.)

These in-depth evaluations must be performed in recognition of the directives and guidance from Air Force leadership and should be done in concert with inputs from the DoE,

other Services, and relevant national organizations. Such a systematic, centralized approach will be important to ensure appropriate system security and cost-effective solutions are implemented. Essential elements of these evaluations include the following:

- A base self-assessment that identifies site-specific opportunities for developing or accessing alternative energy sources. The use of "best practices" should be applied to implementing conservation measures, upgrading energy systems, and planning new facilities.
- A standardized assessment of vulnerabilities and ways of strengthening security (discussed in Chapter 3) and providing for mission-critical energy backup capabilities. The assessment should identify opportunities for incorporating new alternative energy resources into the energy security posture of the base and region.
- A plan for incorporating microgrid and energy storage technologies (discussed in Chapter 4) to improve the control and distribution of energy resources. The ability to operate off of the primary grid while assuring electrical supplies for mission-critical demands will be assisted by microgrid technologies. A centralized evaluation of how to integrate these systems will help augment local technological expertise.

2.4 Recommendation 1: Adopt a Systems Approach to Alternative Energy Projects

As noted in Figure 2-4 (below), the Air Force's significant strides in the alternative energy area came from advances in policy[12] and individual base initiatives.[13] However, neither the policies nor the deployment activities have engendered a systems-level view of which technologies make sense, where they make sense, and what benefits they bring to the Air Force enterprise. Such a systems approach is needed to ensure the Air Force achieves the maximum benefit from these technologies.

As this chapter showed, Base Energy Managers must be supported as they navigate the complexities of advanced alternative energy technologies; cyber and physical security of energy systems; federal, state, and local incentives; interaction with local utility providers; and the development of appropriate contracting documents for awarding alternative energy projects. No one person or even one facility can be expected to have expertise in all of these areas. Without such expertise, the Air Force runs the risk of developing solutions that are not optimal or are perhaps even detrimental from security, cost, and environmental perspectives.

12 Both the December 2008 Air Force Energy Program Management Policy Memorandum (AFPM10-1) and the Air Force Energy Infrastructure Strategic Plan include development and utilization of alternative energy sources as a major component of future Air Force energy use.
13 See Figure 1-2 for a listing of alternative energy projects in the works.

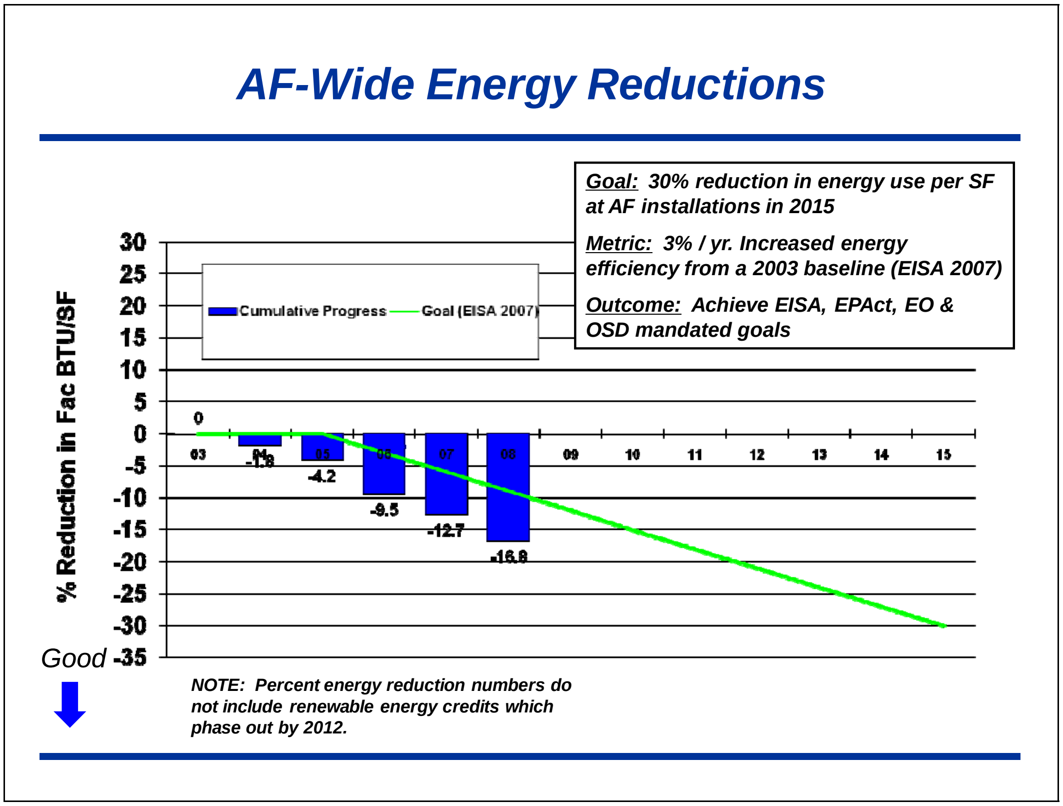


Figure 2-4. Improvements in the Air Force's Energy Picture have been Driven by Both Policy Advances and Individual Base Initiatives. However, a More Robust Systems-Level View is Needed.

As noted in Figure 2-5 (below) Air Force leadership needs to set a clear path forward in providing specific support, training, and guidance to those who will be responsible for meeting its energy goals. Base Energy Managers need access to planning and modeling tools they can use to guide their planning of base energy systems. A Service-wide assessment and energy systems plan needs to be completed for the Air Force to meet its goals. This plan needs to account for local differences and for the state of the art in energy systems and security: topics that are the focus of the next two chapters. As those chapters show, the Air Force must accelerate efforts to understand and plan for updating its energy system. Educating personnel, establishing relationships with the DoE and utilities, and crafting an enterprise-wide plan need to happen sooner rather than later.

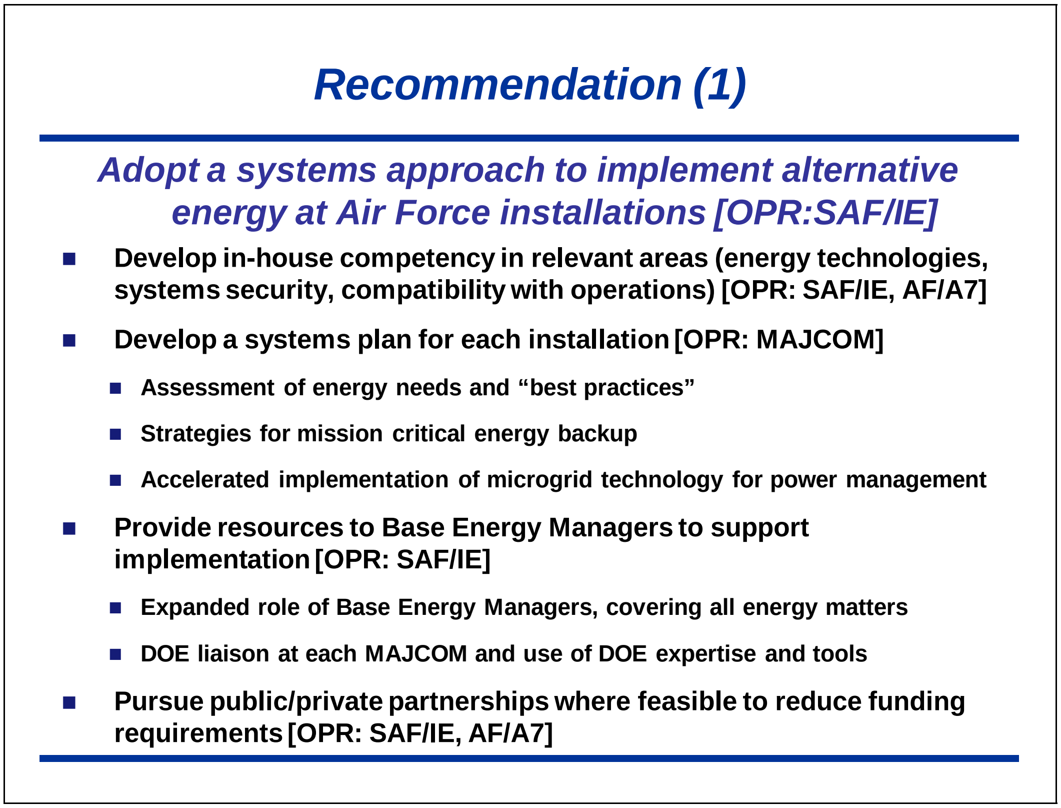


Figure 2-5. Summary of the Panel's First Recommendation.

Chapter 3: Strengthening the Security of Energy Sources and Grids

Nearly all of the power used on Air Force bases for facilities comes from the commercial electrical grid.[14] Figure 3-1 shows how this power is typically delivered to a base. Large commercial power plants send electrical energy through substations and transformers, across transmission lines onto a base. On the base, that power is distributed through the same kinds of electrical grids used across the country. Specifics at each base differ, driving the need for a service-wide assessment. Although this basic configuration has been effective to date, it is neither secure nor "clean" and it does not meet the goals set out for Air Force energy use in current policy guidance.

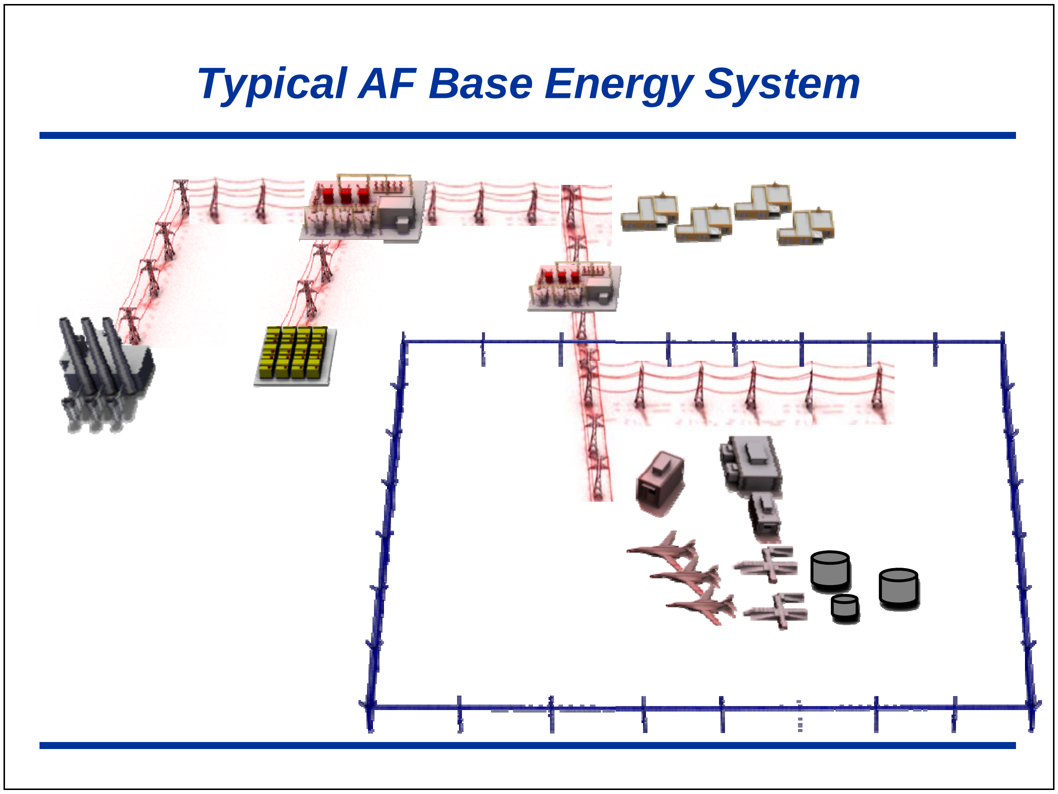


Figure 3-1. Typical Configuration of a Base Energy System.

Figure 3-2 depicts a notional energy system for the Air Force. Some type of alternative energy technology is present on the base—represented in the figure by wind turbines and photovoltaic panels—most likely built from private investment and operated by an independent power production company. Also present on the base is a more advanced control system and power distribution infrastructure, called a "microgrid." Microgrid systems provide the ability to better manage the power distribution on the base and to better match supply and demand.

14 Defense Science Board, 2008.

Another key element of this notional system is energy storage technology, required for matching supply and demand. Such storage technologies allow the base to meet peak demands without adding additional generation and to provide limited-duration emergency backup capability.

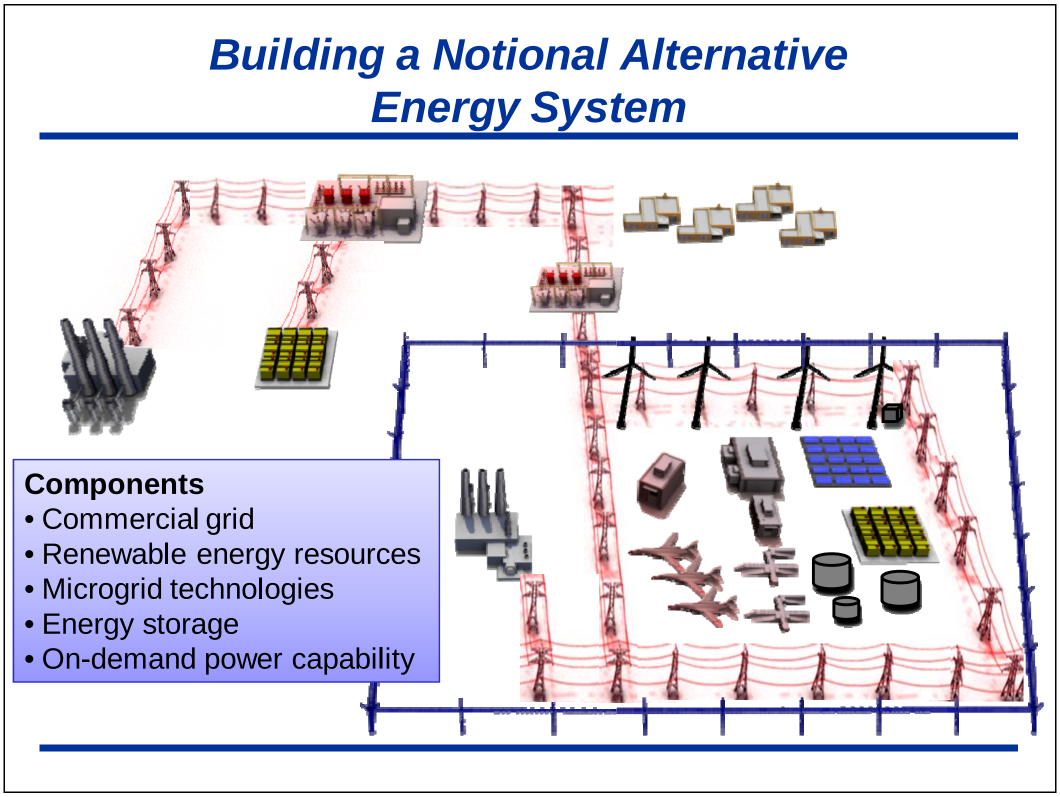


Figure 3-2. A More Diverse, Robust Base Energy System.

The last major element of the notional alternative energy system is essential for independent operation in the event of an extended outage of the local power grid: on-base generation such as the natural gas fired turbine generator implemented at Tinker AFB (discussed in Chapter 1). This addition can provide the base with emergency power during outages as long as the natural gas supply is maintained and not disrupted by the local grid outage or other infrastructure failure.

Overall, this Report describes how such a vision of a notional alternative energy system might be achieved. Chapter 2 described a systems approach to energy for the Air Force. This chapter considers how alternative energy systems can be implemented to enhance energy security for the Air Force.

3.1 Policy Directives for Energy Security Are In Place

The framework for including appropriate security safeguards in energy systems and operations is taking shape within the Air Force slowly. Guidance from the Secretary of the Air Force was promulgated in December 2008 mandating that "…all aspects of energy security…be

addressed to develop and implement comprehensive plans and strategies to enable the Air Force to respond to any energy security threat."[15]

This guidance provides purpose, vision, objectives, and metrics for Air Force energy security policy. It defines roles and responsibilities from Headquarters USAF down to installations. The Undersecretary of the Air Force is designated as the Air Force senior energy official with some duties delegated to the Assistant Secretary for Installations, Environment, and Logistics (SAF/IE).

The Critical Infrastructure Program (CIP) Advisory Working Group is identified as an advisor to the Senior Focus Group on Energy at the Air Force Secretariat level. This group focuses on the identification, prioritization, and analysis of Air Force critical assets and infrastructure dependencies, including energy infrastructure, and determines the impact on Air Force and Combatant Command mission execution if critical assets are lost or degraded.

The current Air Force energy policy directs each installation to determine its own vulnerability to energy interruptions and to ensure plans are in place to mitigate the impact. These plans are supposed to address vulnerabilities due to natural disasters, major system failures, energy supply constraint disputes, and sabotage. The plans are also supposed to identify critical base operations and estimate how long a particular function could be sustained without power. The USAF guidance directs local plans for fighting through such emergencies and a coordinated response with local utilities and community disaster plans. However, in reality installations must rely on subject-matter expertise resident in the CIP Working Group, so individual bases are clearly limited by the pace of the CIP activities.

3.2 Policy Implementation for Energy Security Is Too Slow

While the policy guidance on energy security is clear, implementation plans to convert strategy into action are lagging. The Panel found that the Air Force does not yet have a mature, comprehensive, actionable plan to identify and address vulnerabilities limiting the security of base energy systems.

An early CIP assessment of critical infrastructure[16] was limited in scope, but the trends are worrisome to say the least. Many installations reported aging infrastructure and irregular testing of their backup systems. Of particular concern to this Study are existing vulnerabilities to Air Force installations including but not limited to the following:

- Many bases receive commercial power through single feeder lines or only one electrical substation; these single points of failure are vulnerable.
- Electrical grid control systems are exposed to physical and cyber attacks.
- Critical energy supply chains are susceptible to exploitation and disruption, including single natural gas lines for heating and power generation.

The Panel found the current level of funding for CIP assessments of Air Force bases supports only six assessments per year. At this rate it will take over a decade for the CIP to assess vulnerabilities at all the Air Force installations. Funding at individual installations for local vulnerability assessments is even more difficult to obtain.

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15 United States Air Force: Air Force Policy Memorandum 10-1, 2008.
16 Smith, N., 2009.

The CIP Working Group was directed to partner with appropriate DoD and Department of Homeland Security (DHS) offices to characterize the energy infrastructure outside of installation fence lines. Although these discussions are ongoing with the DoD and DHS on the path ahead to best meet multiple organizational needs, the Air Force is waiting for these discussions come into focus. On the other hand, Air Force Energy Policy personnel have already engaged with DoE's Office of Electricity Delivery and Energy Reliability to assess cyber threats to certain Air Force Bases. Some of these results are described in the 2008 DSB Study on Energy.[17]

The Panel found no systematic, energy security-focused, risk-based management process within the Air Force for assisting base leaders in evaluating current base energy security or with evaluating the implications of integration of alternative energy systems into existing infrastructures.

The emphasis to date has been on the economics of alternative energy and on compliance with a complex of relevant regulations—comprised of a combination of local, state, and federal mandates. As a result, many bases are proudly reporting adoption of renewable energy sources to reduce operating costs and greenhouse gas emissions. Largely absent are analogous stories about improvements in energy security.

An example is the solar PV project at Nellis AFB, described in Chapter 1. This project brings considerable energy savings annually, but it is connected directly to the commercial power grid. As a consequence, it is only as reliable as the existing commercial network and cannot provide power to the base in emergency situations. The failure of the Nellis solar PV project to provide greater energy security for the base illustrates several of the shortcomings of renewable energy projects in general—it is not a unique failure of the Nellis project or base leaders.

Few if any tools exist to aid Base Energy Managers in making informed decisions on alternative energy investments and their impacts on energy security. Furthermore, many risk mitigation possibilities are expensive and there is no accepted cost estimation process in place to aid decision makers. Despite Base Energy Managers' attempts to share lessons learned, most of the subject matter expertise comes from the local utility companies and vendors trying to market their particular type of alternative energy project. Although these individuals are no doubt well-intentioned, energy security may not be their planning and investment priority.

3.3 A Framework for Better Energy Security

From our Study, the Panel derived several important principles that should guide Air Force energy system planners, designers, and operators as part of the enterprise-wide assessment recommended in Chapter 2.

3.3.1 Identify each Base's Critical Operational Needs

Each installation must identify critical functions and operations that would be disrupted in an energy emergency. Funding will be limited in a resource-constrained environment, so each base must develop a prioritized list of vulnerabilities to be addressed at the Major Command level. Centralized risk-management and budget processes should be used to judge where to

17 Defense Science Board, 2008.

commit the Air Force's limited resources. In the case of long-term disruptions, many operations can be moved to another base. However, some functions such as logistics centers or maintenance depots cannot be moved. These bases, in particular, need a plan for long-term energy disruptions.

3.3.2 Train for Outages and Practice for Recovery

Even the best security systems fail. Installation commanders must train for outages and include local utilities and commercial power providers in the exercises. The Study revealed that many backup power systems are rarely turned on. It should be the norm to test all backup systems routinely and know the procedure to restore power before a disruption. Although almost all bases experience periodic power outages due to natural events, intentional disruptions could be more difficult to remedy and much longer in duration. The potential approaches to outages can be broadly grouped into the following two categories: the ability to absorb a blow and recover prioritized mission capabilities quickly, and the ability to degrade operations gracefully and prioritize reconstitution.

Major Command inspection teams and base commanders should work to build and maintain high standards of conduct in the teams charged with fighting through power outages. The reconstitution of power systems after major disruption should be prioritized according to mission-critical functionality.

3.3.3 Diversify Sources of Generation and Distribution

Vulnerabilities arise from the potential for supply chain exploitation and sabotage of material for important operations: fuels for backup generators could be contaminated, critical control systems could be hacked, and exposed single points of failure in the energy supply chain (e.g., single natural gas line or electricity feeder entering the base) could be destroyed.

One mitigation approach is to build in system redundancy by diversifying the commercial energy generation sources and distribution networks. Where appropriate, the Air Force should advocate with local communities for a broadening of the utilities' energy sources. Possibilities include mixes of fossil and nuclear plants and various forms of renewable energy sources—wind and solar being prime examples. Air Force level resources and expertise should be made available for such local advocacy efforts.

Since many Air Force installations are embedded in communities that also require access to assured and affordable power, it makes sense to view the challenge as a system that includes not only the base, but also the surrounding community. Toward that end, we recommend the Air Force broaden its energy strategy to include advocacy for an "Assured National Energy Grid" that would call for local, state, and federal investments to improve the reliability and surety of the national power generation and distribution system. The Air Force should examine the benefits of partnering with other federal installations in the vicinity of bases to share in security costs and benefits. Military bases make ideal hosts for power plants and support infrastructure because some level of security is already provided.

The Air Force should work with power providers to ensure consideration of energy security in planning. This would benefit not only Air Force bases, but also the local community. For example, building in a reserve capability on the part of providers to allow for a direct feed to bases would also provide the capacity for local businesses to grow. The Air Force could seek

legislative action that would provide federal incentives for power providers to provide this excess capacity: this would carry benefits to national security and would help stimulate local and regional economies.

3.3.4 Design for Fail-Secure Operations

As discussed in Chapter 2, the civil engineering community must lay out a conceptual framework to drive a detailed design of the enterprise's overall energy security. This design should include features to insure "fail-secure" operation for the Air Force. Layers of defense should be planned to supply power to the critical operational functions even in the face of external power losses.

3.3.5 Harden Against Physical or Cyber Attacks

All components of energy generation and distribution are vulnerable to exploitation, natural disasters, or neglect. An important principle is to harden various elements of the energy supply system against physical and cyber attacks. A good first step is to bring critical generation and control nodes under secure control by locating them within the base perimeter. Backup generators, fuel supplies, and critical control nodes should be physically protected with limited access. In particularly critical operations it may be appropriate to use administrative controls such as the "two-person concept" to further safeguard the possibility of an energy disruption.

3.3.6 Diversify On-Base Energy Sources

Where possible, the Air Force should plan to diversify on-base energy resources. Some examples include incorporating microgrid technologies, replacing diesel backups with modern power generation equipment, and using smaller-scale alternative energy sources. Microgrids, in particular, are essential for the ability to "island" a base, making it less dependent on the commercial grid and improving reliability.

3.3.7 Use Aviation Fuels for Backup Power

The most common form of emergency backup power for bases is diesel fuel generators. The most common form of fuel on bases is aviation fuel, which cannot be used in diesel generators. The Study found a disconnect between the need for backup power and the inability to use the dominant form of liquid fuel to be a problem and an opportunity. If backup generators could use aviation fuel then most bases would see a dramatic increase in their ability to operate through extended electrical grid outages. Backup generators with the capability to use jet fuels can already be found in the Air Force, particularly outside the Continental United States and in expeditionary units.

Thinking even more long-term the Air Force should consider the use of fuel cells driven by aviation fuel sources. This approach offers clean and efficient power and the potential for combined heat and power for backup operations. In addition, if the operations are critical and a microgrid is installed, these types of systems can be used as main heat and power generation with clearly defined operational performance to meet energy security requirements.

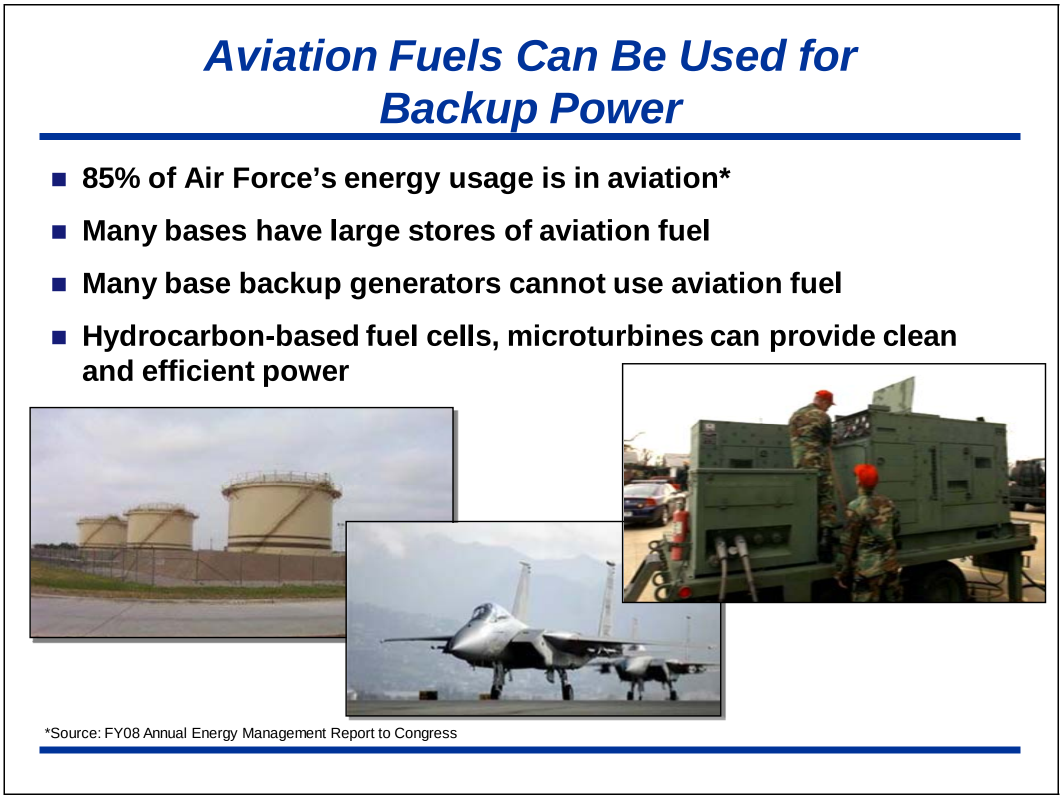

Figure 3-3. The Air Force is the Largest User of Energy in the Federal Government, as the Mission and Global Operations Require a Tremendous Amount of Energy. (In Fiscal Year 2007, the Air Force consumed over 2.4 billion gallons of aviation fuel in at a cost of over $7.7 billion.)

An interesting trend seen in the commercial sector is the location of power generation resources on commercial facilities. This trend is caused by commercial customers' increased need for reliable operations during power outages (e.g., telecommunications facilities, hospitals, large financial institutions). In contrast to the traditional model of a low-efficiency diesel generator, these newer generators are designed with efficiency in mind and are configured to allow the utility to switch them on during periods of peak demand, offloading energy requirements to relax the stress on the existing power transmission grid. The electric utility's rate structure provides an incentive for commercial customers to reduce energy usage during these peak demand periods. Such a model is well-suited to provide increased energy security and potential savings for the Air Force as well.

For the long term, fuel cells powered by aviation fuel offer higher efficiency and cleaner operation and could even become part of a system that can feed energy back into the electrical grid during peak demand periods as a means of offsetting energy costs.

3.4 Recommendation 2: Implement Current Policy on Energy Security

Air Force policy for security of its energy is clear and current. The Panel found, however, that the Air Force does not yet have a mature, comprehensive, actionable plan to identify and address the vulnerabilities limiting the security of base energy systems. The Panel

recommends the Air Force take immediate, appropriate actions to implement the current policy guidance on energy security.

Recommendation (2)

Implement current policy guidance on energy security [OPR: SAF/IE, AF/A7]

- **Develop a mission-critical priority list and accelerate vulnerability assessments of bases [OPR: SAF/IE, AF/A7]**
- **Develop risk mitigation strategies [OPR: SAF/IE, AF/A7]**
  - **Implementation of microgrid technologies**
  - **Diversified energy sources and connections to the regional power system**
  - **Capability to run base backup generators on jet fuels; expanded and hardened fuel storage capacity**
  - **Hardened power systems and grid controls against cyber, physical disruptions**
- **Practice "fighting through" an energy system disruption during base exercises [OPR: MAJCOM]**
  - **Graceful failure and rapid recovery modes for:**
    - **Mission-critical operations**
    - **Operations support**
    - **Base and local support**

Figure 3-4. Summary of the Panel's Second Recommendation.

As a first step, the Air Force should establish an operational risk framework against which to judge energy security vulnerability and to conduct design tradeoffs against consequences. This framework should be part of the systems approach and should provide the means to rank facilities in accordance to vulnerability and consequences of failure. Some work in this area has been done by the CIP Working Group, but the Panel recommends the Air Force accelerate the pace of assessments and provide funding to implement the necessary security improvements in order of mission criticality.

Guided by the risk assessment, the Air Force should begin to build an in-depth defense and sustainability posture appropriate for each facility and each installation. As part of its planning, the Air Force should consider the acquisition and installation of microgrid systems on bases. These systems are necessary to effectively integrate alternative energy sources into an established base power system and, if appropriately designed, can add a layer of security by automating power switching during outages.

The Air Force also needs to diversify energy, both in generation and distribution. Air Force bases are part of a local community and base commanders should lend their voice to public discussions on diversification of the commercial energy supply and grid system, seeking alternative energy sources and on-base distributed grids for some locations.

As noted above, most bases rely on stand-alone generators for backup power and most of these run on diesel fuel. The Study Panel recommends that part of the risk assessment consider fuel capacity needs to provide for extended outages. More attention needs to be paid to hardening the backup fuel storage system. This should include attention to limiting the opportunity for insider disruption or sabotage such as contamination of the fuel supply.

For the longer term, the Panel recommends the Air Force take steps to use aviation fuel as a source to power backup generators. This will mean modifications or replacement of existing generators. All new generators should be acquired with an aviation fuel option and microgrid operation in mind.

Finally, wherever possible, steps should be taken to harden power generation, switches, transformers, storage, and distribution systems against physical and cyber attack. Simple steps such as improving physical barriers, moving security fences, installing locks, and further limiting access to critical energy control points should be encouraged and tested.

Given the critical dependence on the fragile and vulnerable commercial grid, the Air Force must be prepared to fight through energy disruptions, natural and man-made, short-term and long-term. Planning for graceful degradation during power outages will require investments in smart microgrids and monitoring systems, redundant distribution lines and switches, power storage systems, and distributed power generation systems. The Panel recommends accelerating the pace and scope of the CIP Working Group assessments.

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Chapter 4: Pursuing Alternative Energy and Storage Solutions

Alternative energy sources bring challenges. Of the challenges, the lack of available and cost-effective energy storage systems that adequately compensate for variations in power output (on the supply side) and power usage (on the demand side) is critical for the Air Force. The inability to manage output from intermittent sources (such as solar and wind power) is a systems-level problem that limits the ability of such alternative sources to provide bases with a capability for grid-independent operation. This chapter makes recommendations regarding selecting alternative energy generation systems and how to overcome some of the associated challenges. A more detailed summary of these technologies are in the appendices to this Report. Also, the Panel's cursory cost minimization analysis of 87 bases may be found in the earlier version (For Official Use Only) of this Report. The Study Panel envisions this as a starting point for the detailed system-level planning we recommended in Chapter 2.

4.1 Selecting Alternative Energy Generation Systems

A myriad of alternative energy sources exist at varied levels of technical readiness from early development to full commercial implementation.

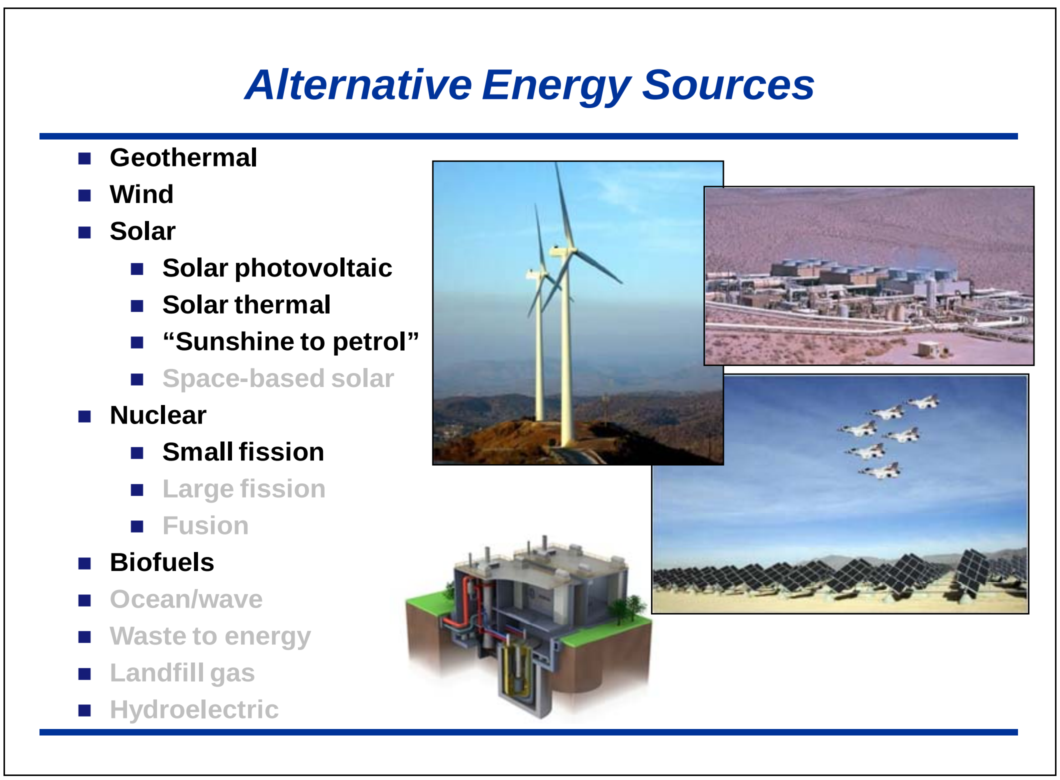

Figure 4-1. List of the Alternative Energy Sources Reviewed. (Sources in boldface are those recommended for Air Force consideration by the Panel.)

The Study Panel reviewed all of the technologies listed in Figure 4-1 above. A detailed summary of the Panel's findings regarding each technology is available in Appendix A. The relatively mature sources appearing in bold are the ones the Panel recommends as the best opportunities to meet Air Force energy needs and requirements in the near- to mid-term. They share the common feature that, when used in combination with one another and with conventional energy sources, they can fulfill the energy requirements for a large number of different bases while meeting the Air Force's stated environmental goals. Nuclear, because it can stand alone and operate for long periods without refueling, has the added advantage of not requiring energy storage. Chapter 5 discusses the possibility for nuclear energy in more detail.

Alternative Energy Resources-Summary

Energy Technology	Security	Siting considerations	Storage options	Grid integration considerations	Maturity level	Cost ($/MWh) *
Wind	🟢→🟡	🟡	🔴	🔴	🟡	🟢
Biomass	⚪	🟡	🟢	🟢	🟢	🟢
Geothermal	🟢	🟡	🟢	🟢	🟡	🟢
Solar PV	🟢→🟡	🟡	🔴	🟡	🟡	🔴
Solar Thermal Trough	🟢→🟡	🟡	🟡	🟡	🟡	🟡
Small Nuclear	🟢	🟡	🟡	🟢	🔴	⚪
🔴	Vulnerable in 2 or more following areas: Generation, Supply, and/or Distribution	N/A	None, very limited, or technology under development	Does not usually match load	Designs in place, but not currently licensed	200+
🟡	Vulnerable in 1 of 3 following areas: Generation, Supply, and/or Distribution	Works in limited regions, or in many regions but with complexities.	Storage from 6 Years (Solar Thermal Trough) to 20 Years (Small Nuclear)	Generally matches load, but with grid stability concerns	Few installations are incorporating these technologies	160-200
🟢	Mostly secure, but with potential distribution vulnerabilities	N/A	Continuous or frequently naturally replenished	Operates at high capacity factor, can be base load	Little or no impact to current infrastructure	50-160

Figure 4-2. Summary of the Panel's Evaluation of Alternative Energy Resources.

Some of the technologies listed are suitable only in specific geographic locations. For example, the amount of wind energy available varies from location to location. Maps of wind resources showing good and bad locations are widely available and should be used during the enterprise-wide energy systems review (called for in Chapter 2). Likewise, solar photovoltaic systems obviously require sunlight so they are cost effective only in locations with high probabilities of cloud-free lines of sight to the sky.

The cost of the technologies, particularly the cost to produce a given unit of electricity, is highly variable from technology to technology and location to location. Environmental impacts, the amount of land needed, impacts on other base operation systems (such as air traffic control radars), and other factors all affect the utility of these technologies. The systems-level approach recommended in Chapter 2 will help the Air Force in planning for alternative energy implementations.

4.2 Selecting Electric Storage Technologies

A key element required to improve the energy security posture of Air Force installations is energy storage. Storage systems are needed if bases are to operate during extended periods without the local commercial grid. The two central reasons for energy storage for renewables are intermittency and the mismatch between supply and demand:

Intermittency: All renewable energy sources are intermittent in their ability to produce energy. For example, solar energy is unavailable at night, and is reduced by cloud cover, shading, seasonal variations, and air turbidity during the day. Wind energy also varies according to the weather, the time of day, and also cyclically (typical variation between one and three weeks). Although hydro power is generally more stable, it does vary seasonally according to the water balance. Storage systems mitigate the impact of the intermittency of large-scale renewable power sources.

Production and Load Mismatches: Often users need energy when the renewable resource is either (1) not able to produce the energy or (2) is unable to produce it in the amounts needed to meet demand (e.g., solar energy at night or wind energy on a calm day). The mismatch between the rate of production and energy demand means most renewable energy technologies rely on storage or on backup sources from elsewhere on the energy grid to be viable at a large scale. Energy storage balances alternative generation sources and energy loads to achieve a reliable power supply when either the demand exceeds supply or when the main supply is disrupted.

Energy storage adds benefit when applied to either traditional or renewable energy systems. Ideally the selected storage technologies will shave the peak load, saving excess energy and, thus, reducing the size of the total generation system required. Wind and solar energy sources, in particular, require smoothing of fluctuations during energy generation to store excess energy (see Figure 1-4 for a graphic representation of this concept). Without storage, renewable sources require augmentation with large backup sources (e.g., gas turbines) for grid-independent operations; this makes investments in the renewable energy source less attractive.

Energy storage solutions also rely upon the ability of the energy grid to efficiently transport energy between the generation and storage location(s). In many regions of the country, for example, wind resources are located in areas with inadequate transmission capability. In these cases, the power provider might have to co-locate the storage system with the wind turbine facility as a cheaper alternative than upgrading the transmission grid.

For the Air Force, this co-location model brings an added benefit of increased energy security, if properly implemented. By having both the generation source and storage system located on a base, the ability to operate independently is increased (assuming the microgrid control system is configured to allow the on-base systems to feed power directly to the base). A similar model could also apply to large scale solar electricity installations like the one at Nellis AFB, with proper planning.

This Study followed a 2008 DoE Electrical Advisory Committee examination[18] of mature and developing energy storage technologies. Figure 4-2 below provides a general comparison of the characteristics of the various technologies, including batteries, thermal storage, compressed air, pumped water, flywheels, superconducting magnetic systems, hydrogen production, and fuel

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18 United States Electric Advisory Committee, 2008.

conversion. An overview of each type of storage system and discussions of microgrid technologies reviewed by the Panel are available in the appendices.

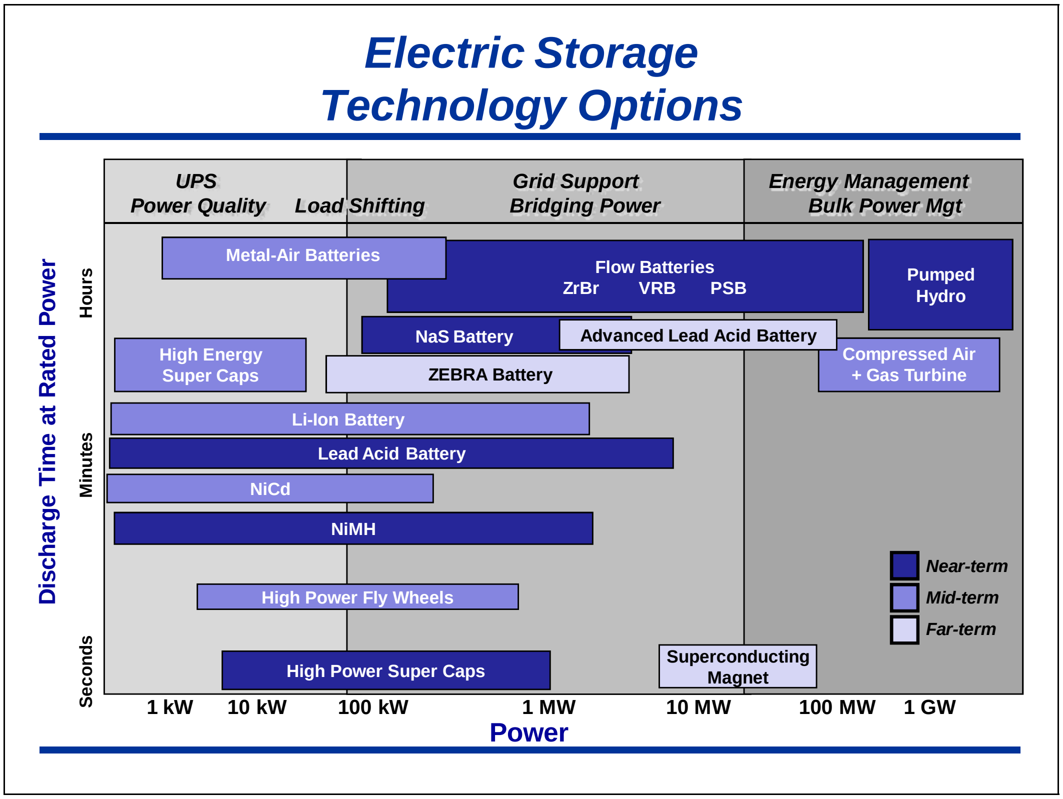

Figure 4-3. Summary Slide Showing Capacities, Discharge Rates, and Technological Maturity of Electrical Storage Options Considered by the Panel.

Current utility-scale implementations are mostly electric batteries, pumped water, or compressed air energy storage systems. For example, since 2006 American Electric Power (AEP) has used a 1.2 MW sodium-sulfur battery system near Charleston, West Virginia, with a capability to supply 7.2 MW per hour of energy. According to AEP, the peak-shaving unit is expected to last 15 years, or 4,000 to 5,000 charge-discharge cycles at 90 percent of full energy capacity. This would be an appropriately-sized solution for many installations.

About 3% of the total power delivered by the nation's grid (18,000 MW) is supplied through pumped water energy storage facilities: water is pumped to a high reservoir during high generation periods and is then released to a lower reservoir through a hydroelectric generation system to generate electricity when needed. The geographic demands of such a storage system make it inappropriate for many locations.

Hydrogen fuel cells may also be used for back-up power. These systems tend to be more competitive for large power storage needs, but they require the supply and storage of hydrogen. A similar technology, hydrocarbon fuel cells, is discussed below as a promising technology for Air Force application.

The main disadvantage of energy storage is the loss associated with converting energy from its original state to a state than can be stored. For example, Compressed Air Energy

Storage (CAES) pre-compresses and stores air to use as fuel to spin a turbine to generate electricity when needed. But CAES systems burn a mixture of the compressed air and natural gas when generating power, so emit carbon during the conversion cycle. CAES technology requires further evaluation and is highly dependent upon the cost of preparing underground caverns or other geophysical domains for compressed air storage.[19] Likewise, rechargeable batteries are typically only 85% efficient in storing electricity. In some cases the final usable form of the energy is different from both the stored form and the original form (e.g., power from a wind turbine pumps water uphill which is released later through a hydro-electric turbine to generate power). Each conversion incurs additional operational and efficiency costs.

4.3 Backup Storage for Base-Level Operations

For the Air Force, energy storage systems serve dual purposes: power to bridge alternative energy systems with intermittent, under-, or over-production periods (like wind and solar) and power backup for covering outages.

The Panel considered ways of bridging base power losses for short periods of time up to several hours. The Panel found most bases need systems providing power in the 100 KW to 40 MW range for these shorter time periods. Each of the systems considered has its own niche applications. For example, rechargeable nickel-cadmium and other metal-based batteries power computers and servers during short term power outages. Battery back-up systems could also bridge power output from alternative energy systems and, therefore, should be an integral part of each base's energy system. For many short-term power needs, batteries provide the most obvious, currently available solution. They are very efficient storage media, with efficiencies as high as 90%, but they suffer from the fact that they last a finite number of charge/discharge cycles so replacement costs must be considered in planning and budgeting processes.

Pumped hydro systems could provide reliable longer-term energy for base or regional power grids when demanded. It is vital the possibilities and rationales for such storage systems are considered during the enterprise-wide review called for in Chapter 2. For example, it would not be reasonable to build hydro systems at every base, but the enterprise's operational fail-secure plans should account for where such reliable, long-term solutions are appropriate.

For longer outages (hours or days), the Panel found that liquid fuel-powered turbine generation systems are attractive because of the falling emissions footprint and the possibility of using the abundance of jet fuel on many bases.

There are large, international investments in all of the storage technologies discussed above. The Air Force maintains a robust Science and Technology (S&T) presence in rapid discharge, high energy density capacitors that would be needed for pulsed power applications such as directed energy weapons. Apart from this investment, and the energy-to-liquid fuels capability described below, the Panel does not recommend the Air Force invest in research into new energy storage technologies. The Panel recommends the Air Force monitor and harvest relevant industry advances as they become commercially available.

19 United States Air Force: Air Force Policy Memorandum 10-1, 2008.

4.4 Hydrocarbon Fuel Cells as Efficient Base Energy Sources

A fuel cell is an electrochemical energy conversion device that directly produces electricity. It is essentially a battery, except it oxidizes a fuel (hydrogen or a hydrocarbon) instead of oxidizing and reducing metals and metal salts as in other batteries. Fuel cells consist of two electrodes sandwiched around an electrolyte. The fuel is fed into the "anode" and oxygen enters the fuel cell through the cathode. In the case of a hydrocarbon fuel, the reaction produces protons, carbon dioxide, and electrons. The electrons are collected on the electrode and produce the electric current for the system. To complete the circuit, electrons flow through the electric load to the cathode, where oxygen molecules are reduced and combined with protons from the anode reaction to generate water.

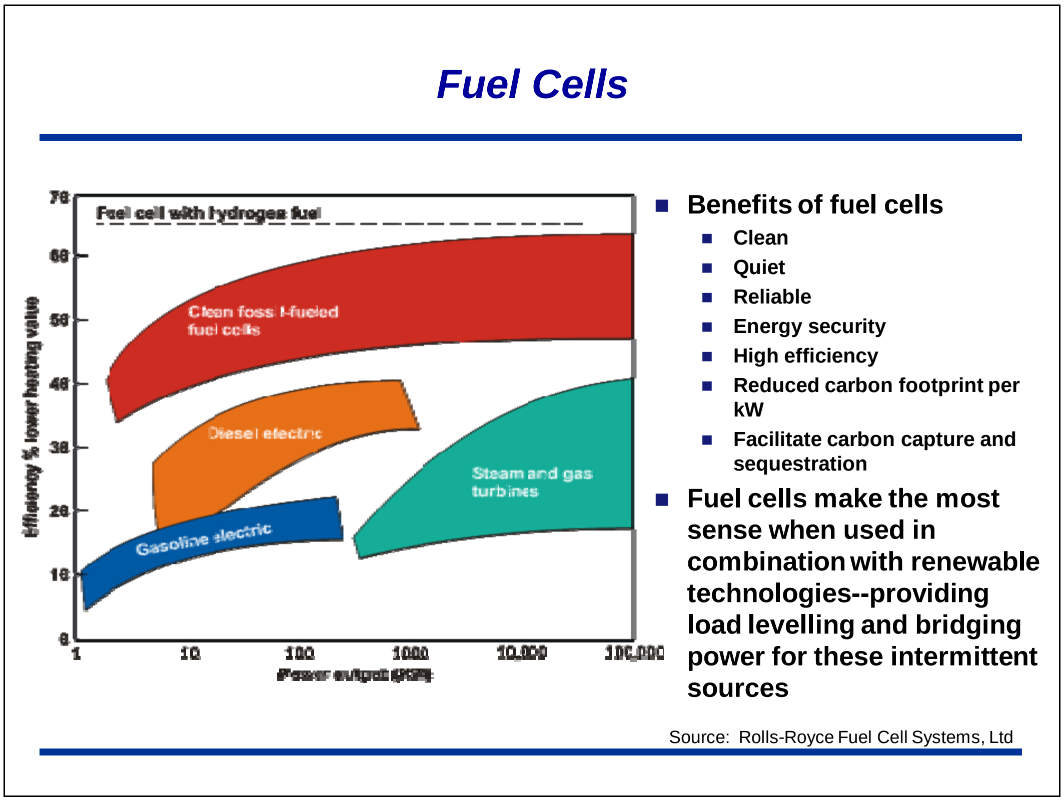

Figure 4-4. Fuel Cell Technology Comparison: Efficiency versus Power Output.

At present most fuel cell systems are limited in the amount of current they can generate and the longevity of the electrodes. Systems have been demonstrated with conversion efficiencies as high as 60% and, theoretically, higher;[20] by contrast, the efficiency of burning the hydrocarbon in a turbine system to generate electricity is closer to 40%. A fuel cell's improved efficiency, along with a significant reduction in nitrogen oxides and other polluting by-products of combustion, provide drivers for development of the technology. Substantial research and development of fuel cell systems is underway, nationally and internationally.

There are a number of fuel cell types. For stationary power applications, solid oxide and molten carbonate fuel cells are the most common. These fuel cells operate at high temperatures

20 Milewski et. al., 2009.

(between 600 and 1,000 degrees Centigrade). This high temperature makes reliability a problem because components can break down after cycling on and off repeatedly. However, when in continuous use solid oxide fuel cells have been found to be the most stable type. The high temperature also has an advantage: the steam produced by the cell can be channeled into turbines to generate even more electricity. This process is called co-generation of heat and power, and it improves the overall efficiency of the system.

Fuel cells are commercially available from 100 KW – 50 MW and offer many advantages over generators and gas turbines. They are reliable, relatively quiet, and much cleaner since the byproducts are not generated by flame combustion. Lower emissions of pollutants such as nitrogen oxides and sulfur oxides and lower emissions of carbon dioxide per watt of electricity are achievable. The greatest advantage is efficiency, which exceeds hydrocarbon-fueled combustion technologies over a broad range of outputs.

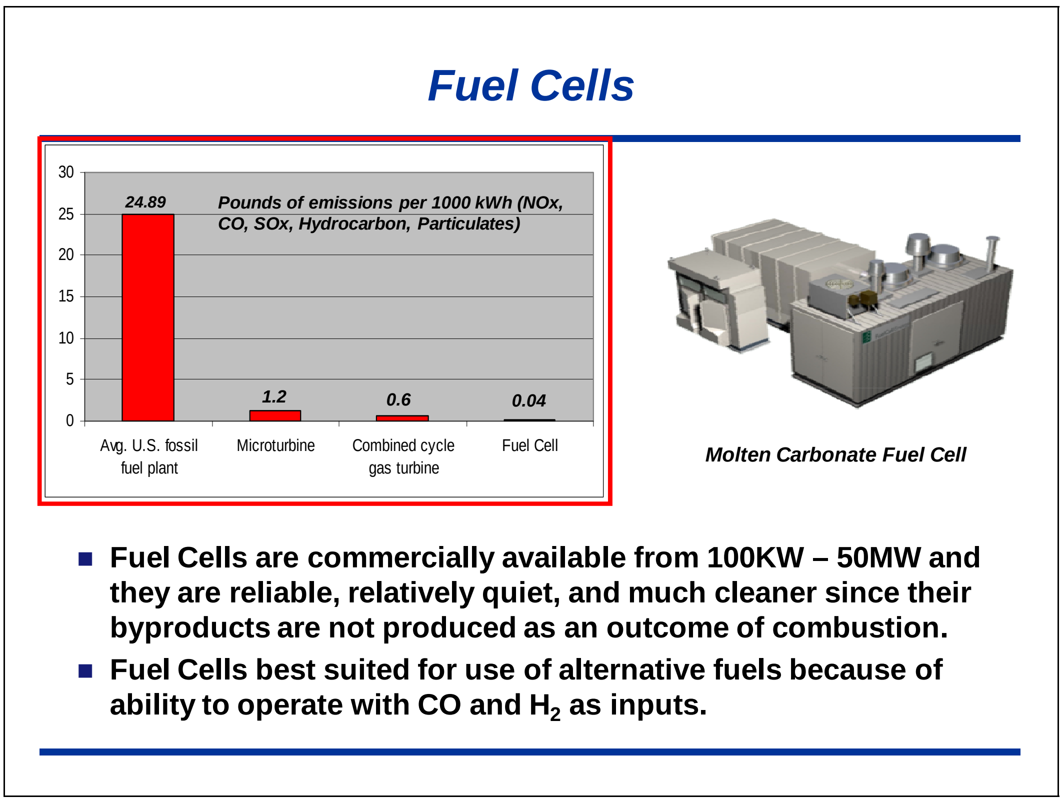

Figure 4-5. Fuel Cells are Not Only Efficient, but Also Emit Relatively Little per Kilowatt Hour.

A drawback for high power applications of fuel cells is the inability to cold-start the system. Thus a high operating temperature must be maintained if it is to be used as an on-demand or load-following power source. Unlike batteries or capacitors, hydrocarbon fuel cells cannot “run backwards,” or recharge. They require a constant supply of hydrocarbon fuels. A significant question with hydrocarbon-based fuel cells is electrode lifetime under field operating conditions. High-power applications of hydrocarbon fuel cells have not yet been demonstrated over long periods. Also, the electrodes are susceptible to “poisoning” by sulfur compounds, necessitating the use of scrubbers in-line with the fuel system. Nevertheless,

hydrocarbon-based fuel cells or high efficiency turbines, the closest competitor to fuel cells, should be considered to play a key role in base energy systems.

4.5 Renewable Options for Liquid Fuel

The Panel found the most widely used backup power sources are liquid fueled generators. Technologies to generate liquid fuel from local power sources, although less technologically mature, have huge potential benefits for Air Force installations. Of note, the minimal sulfur content of synthetic fuels makes these fuels particularly attractive for hydrocarbon fuel cell applications because fuel cells are easily "poisoned" by sulfur.

In the United States, alternative approaches for liquid fuels include processing from biomass, coal, and wastes. Most approaches involve preparing and feeding the matter into a pressurized gasifier to produce synthesis gas, the important constituents of which are hydrogen and carbon monoxide.

4.5.1 Fuel Synthesis from Air: "Sunshine to Petrol"

A novel process being developed at Sandia National Laboratories uses concentrated solar power to convert what are normally combustion products (carbon dioxide and water) into synthesis gas, which can then be converted to virtually any liquid fuel using established processes. This "Sunshine to Petrol" concept[21] uses a high temperature catalytic reaction to split the chemical bonds to create synthesis. The basic idea is to reverse the combustion process, recovering the building blocks of hydrocarbons. Because it recycles carbon dioxide as a reactant, the process can also help reduce greenhouse gas emissions, thereby helping to achieve another target of the Air Force Infrastructure Energy Strategic Plan.

Sandia Laboratories' process (Figure 4-6 below) uses a solar reactor to split carbon dioxide into carbon monoxide and oxygen. A solar furnace (Figure 4-7 below) sends intense sunlight into the prototype, heating rotating cobalt ferrite rings to about 1,427 degrees Centigrade, causing the release of oxygen. The rings are then allowed to cool to about 1,093 degrees Centigrade, at which point they are exposed to carbon dioxide. An oxygen atom from the carbon dioxide molecule combines with the cobalt ferrite, restoring it to its original state, and, thus, enabling another cycle. Carbon monoxide is left behind, and this is then used as a building block for synthesizing the hydrocarbon chains for the synthesis gas.

One of two conventional processes may then be used for converting synthesis gas into liquid fuels: the Fischer-Tropsch method or the methanol-to-gasoline liquefaction method.[22] The Fischer-Tropsch method was invented in Germany during the 1920s and is in commercial practice in South Africa. Both approaches start with synthesis gas, remove the impurities and carbon dioxide, and use a catalytic reactor to produce liquid hydrocarbons. In a Fischer-Tropsch plant, the synthesis gas is converted to high-quality diesel and jet fuels that can be used directly for the on-base applications discussed in this Study. In other words, the product of the Fischer-Tropsch plan can provide jet fuel and can provide backup power generation for facilities with generators.

21 Sandia National Lab, 2007.

22 The Mobil Research and Development Corporation invented the methanol-to-gasoline (MTG) approach in the early 1970s. In an MTG plant the synthesis gas is first converted to methanol and this is then converted to a mix of hydrocarbons similar to those found in gasoline.

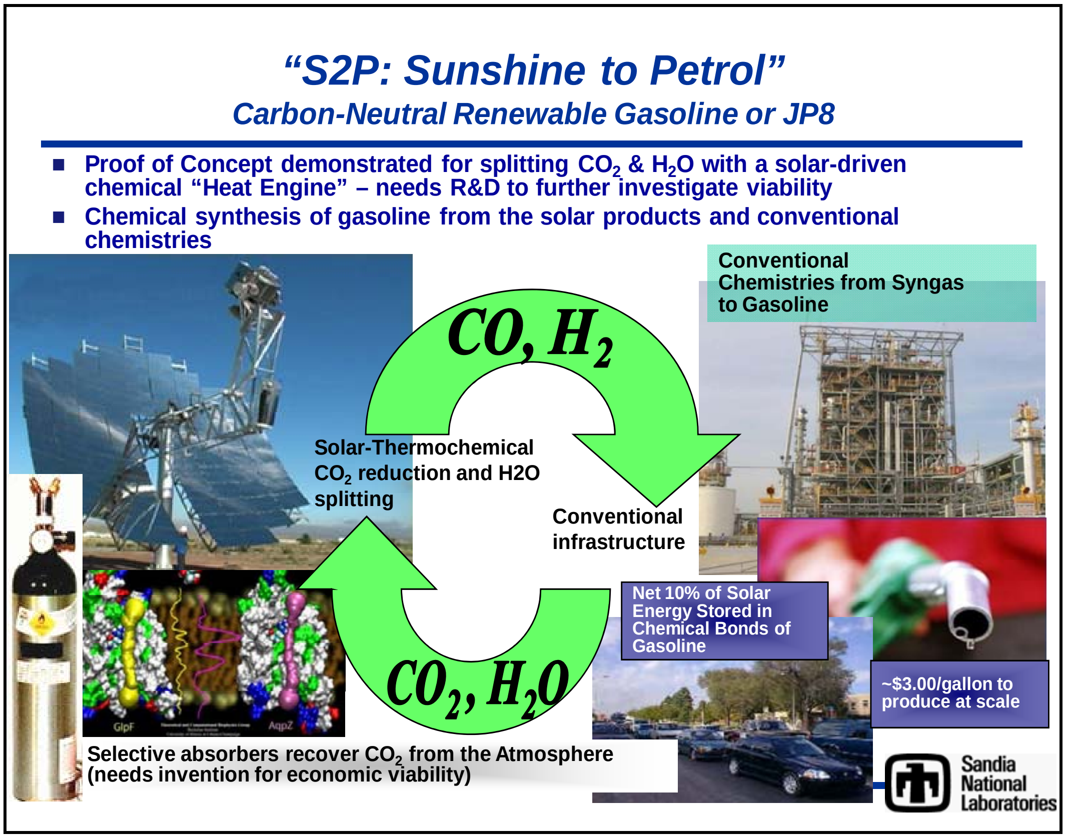

Figure 4-6. A Summary of Sandia Laboratories’ “Sunshine to Petrol” (S2P) Initiative.

Figure 4-7. Sandia Researcher Rich Diver Checks the Solar Furnace which will be the Initial Source of Concentrated Solar Heat. (Eventually parabolic dishes will provide the thermal energy.) [Photo by Randy Montoya]

4.5.2 Biological Fuel Synthesis

Under a directive from the Secretary of the Air Force, the Air Force is considering biological feedstocks to produce synthetic jet fuel.[23] The program examines hydro-treated jet fuel in which impurities (especially sulfur) are stripped by the fuel's reaction with hydrogen. Several different categories of biofuels exist:

- First-generation (or lignocellulosic) biofuels are made from carbohydrates, oils, or fats using existing technologies. Vegetable oils can be heated, and animal fats can be hydrogenated to provide fuel-quality substitutes. However, one problem with most first-generation biofuels is a potential increase in greenhouse gas emissions resulting from land use changes if certain feedstocks were to be mass produced for this purpose.
- Second-generation biofuels are made from non-food crops, mostly waste biomass. These typically use biomass-to-liquid technology.
- Third-generation biofuels use algae or algae products such as oils. Algae provide high-yield feedstocks to produce several dozen times more energy yield per acre than first-generation feedstocks.

The main bottleneck for the production of lignocellulosic biofuels is the lack of technology for the efficient conversion of biomass into liquid fuels. Much of the current effort has focused on conversion to ethanol, but less has been invested in studying new technologies for conversion to gasoline, diesel, and jet fuel.

In 2007, the National Science Foundation and the Department of Energy produced a roadmap to the next generation of biofuel refineries.[24] Several new technologies were emphasized, including the following with possible applicability to the Air Force:

- Selective thermal processing of lignocellulosic biomass in distributed refineries,
- Adaptation of existing petroleum refineries toward conversion of biomass-derived oxygenates,
- Liquid phase processing of biomass-derived sugars to hydroxymethylfurfural (HMF), followed by HMF conversion to diesel or jet fuel,
- Process intensification of diesel and gas production from carbon and hydrogen using Fisher-Tropsch synthesis, and
- Use of nanotechnology, quantum chemistry, and synthesis methods to design recyclable, highly active, and selective heterogeneous catalysts for biofuel production.

Algae naturally produce oils, but growing algae and extracting its oil is expensive and time-consuming. Current technologies produce biofuels from algal sources at a cost of roughly \$400 to \$1,600 per barrel; to be price-competitive with oil, the cost will need to drop by roughly a factor of ten. The algal oil is contained within the cell walls, so extraction and separation processes need to be devised. Typically, the oil is extracted using a mechanical press and the pulp is treated with a solvent to remove any remaining oil. Such a process is energy intensive, and alternative methods are under development. For example, ultrasound and an electromagnetic pulse have been used to break the algal cell walls. The solution is then infused with carbon

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23 See Aimone, Michael, quoted in Farivar, 2007.
24 National Science Foundation, 2007.

dioxide, lowering its acidity and separating the biomass from the oil.[25] Another more speculative approach is to genetically engineer new kinds of algae that secrete oil.

An April 2007 report from the Environmental Protection Agency (EPA) presented opportunities for and benefits of using anaerobic digesters at wastewater treatment facilities to provide combined heat and power that, in principle, can provide low cost renewable energy to reduce greenhouse gas emissions when compared to conventional sources.[26] The digesters provide biogas that can be used as fuel for a generation system. The thermal energy produced can be cycled back to meet digester heat requirements, with the remainder being used for space heating. A typical wastewater plant processes 100 gallons per day of wastewater for every person served, which translates to approximately 2.2 watts of power generation potential per person served per day. The heating value of the biogas produced by the anaerobic digesters is approximately 600 British thermal units (BTU) per cubic foot. So, for each 4.5 million gallons of wastewater per day, the generated biogas can produce approximately 100 KW of electricity and 12.5 million BTU of thermal energy.

4.6 Recommendation 3: Develop and Implement Energy Storage Technologies

Recommendation (3)

Develop and implement energy storage technologies for alternative energy [OPR: AFRL]

- **Near-term technologies [OPR: MAJCOM]**
  - **Incorporate energy storage systems for load levelling and to bridge power from wind, solar projects; integrate with emergency backup where feasible**
- **Mid-Far-term technologies [OPR: AFRL]**
  - **Partner to develop technologies that harness renewables to generate aviation fuels as a high energy density storage medium**
    - **Biofuels to produce aviation fuels**
    - **Synthetic fuels derived from renewable or carbon neutral sources**
  - **Partner to develop technologies for hydrocarbon fuel cells to exploit aviation fuels**
  - **Monitor and harvest R&D into technologies that reduce costs and increase manufacturability of batteries and thermal storage media**

Figure 4-8. Summary of Recommendation 3.

25 Heger, 2009.
26 United States Environmental Protection Agency, 2007.

Energy storage technologies are a critical component of the implementation of an alternative energy strategy. Both near-term and longer-term technologies must play a central role in moving the Air Force toward both increased energy security and reduced reliance on traditionally-produced fossil fuels. Both of these goals must address energy storage as a crucial element.

4.6.1 Upgrade Base Backup Power Systems

Multiple studies over the past decade[27] have identified the Air Force's vulnerability to either temporary or prolonged energy disruption due to natural or manmade causes. Even during normal operations, the Air Force's increasing reliance on intermittent alternative energies (wind, solar, ocean wave, etc.) will require stored energy and upgraded microgrids on installations.

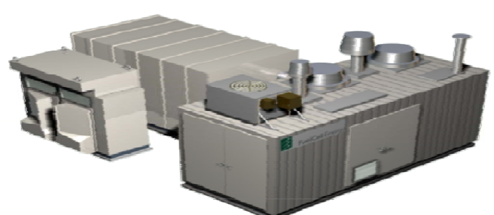
The integration of energy storage with backup systems can be achieved in the near term to provide energy surety for bases. Backup power generators can meet the needs of the airbase and can operate on jet fuel, as discussed in Chapter 2. In the near- to mid-term, battery technology has matured enough to be used in coordination with power generators. Air Force facilities should be willing to host such assets where appropriate. Likewise, hydrocarbon fuel cells offer an efficient, low-polluting possibility for local power generation, both as emergency backup and for electrical grid support.

Molten Carbonate Stationary Fuel Cell
Barksdale AFB, LA

Goals: Install reliable, grid-independent, environmentally clean Molten Carbonate Fuel Cell technology by demonstrating a 300kW to 2MW system at Barksdale

Configure compatible fuel cell stack designs for modularity and expansion.

Conduct future expansion that will include thermal recovery of heat for use within base facilities and possible production of hydrogen.



Milestones

- Introduce Molten Carbonate Fuel Cell technology to AF/Barksdale AFB
- Initial production of 300kW grid power, expand system to 1-2MW
- Recover heat to be used in facilities
- Plan for future configuration to support H_2 vehicles and aircraft support equipment

Figure 4-9. Summary of the Fuel Cell Project at Barksdale AFB, Louisiana.

27 Defense Science Board, 2008.

4.6.2 Invest in Renewable Sources of Aviation Fuels

Fuel constitutes 85% of the Air Force's energy usage.[28] New sources for the production of synthetic jet fuel are gaining importance.

The Panel recommends the Air Force invest and partner in technologies that harness renewables to generate synthetic aviation fuels. Because there is already extensive government and private funding for research and development in this area, the Panel recommends partnering with others, thereby creating a multiplier effect with Air Force research funds.

Research on the conversion of solar photons or other alternative energy source into synthetic liquid fuel (for example, "sunshine to petrol" and algal biofuels discussed earlier) offers the potential to generate jet fuel on any base with access to water, carbon dioxide, and sunlight or other alternative bio sources. This would be an excellent area for increased Air Force R&D investments.

4.6.3 Monitor and Harvest Battery and Thermal Storage Technologies

Both battery and thermal storage will be extremely important for the Air Force to achieve base energy systems to meet its needs in terms of security and reliability. There is substantial private and federal investment underway in battery manufacturing technology as well as research in advanced batteries. Similarly there is government funded R&D in thermal storage media development. For both of these important areas, the Panel recommends that the Air Force monitor and be prepared to utilize advancements to improve its energy systems.

28 Aimone: Alternate Sources of Energy for U.S. Air Force Bases, 2009.

Chapter 5: Evaluating Possibilities for a Nuclear Energy Future

The notional energy system for an Air Base earlier in this report (Figure 3-2) stressed the need for on-demand power to back up the renewable energy systems, even if storage is included in the base's energy system. In order to provide for independent operation an on-demand power plant on base is required to meet the demand for long term outages. Presently natural gas or liquid fuel fired turbines are attractive options to meet this need. However, the natural gas (or liquid fuel) supply cannot be assured unless it is stored on base, and in that case it has a finite limit. Furthermore, environmental issues and carbon emission standards limit these possibilities. The remaining major option for on-base, on-demand power is a small nuclear power plant. There is a growing national and international recognition that nuclear power is an alternative energy source worth including in plans for meeting future energy needs. The Panel evaluated the global status of nuclear power and then considered the pros and cons of this energy source for possible siting on Air Force bases.

5.1 Why Consider Nuclear Energy for On-Base Power?

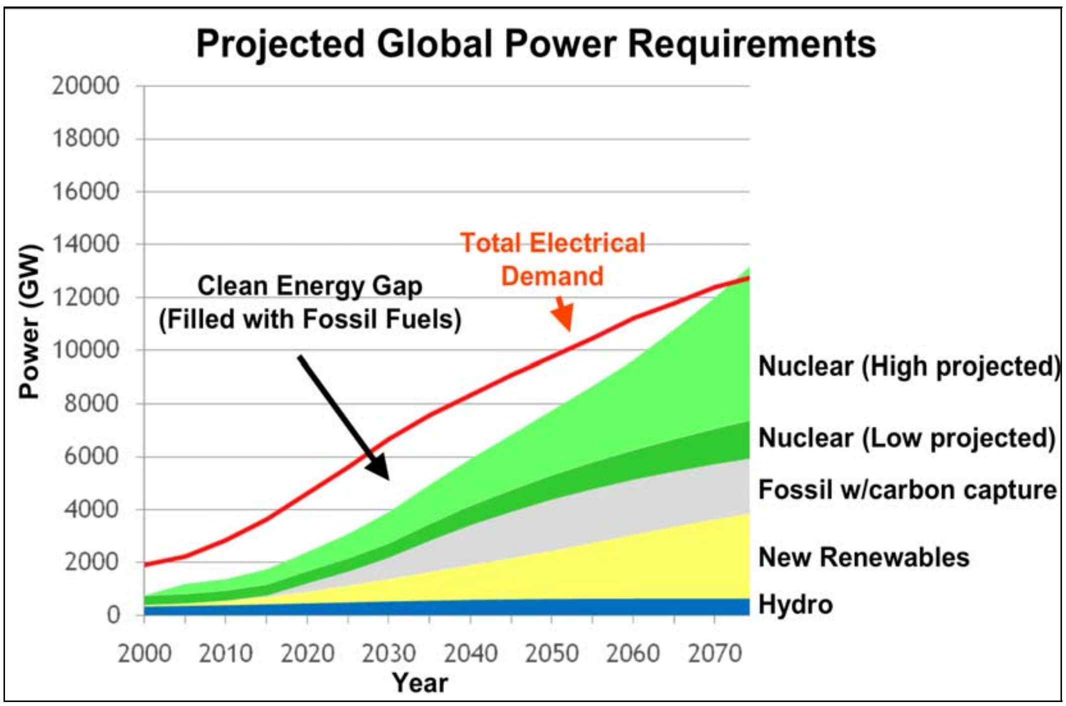


Figure 5-1. Electrical Demand and Anticipated Sources.

Electricity is rapidly becoming the most convenient form of energy. Although future estimates of global electricity vary widely, massive increases will likely be needed over the next several decades.

The graph in Figure 5-1 above is based on estimates from the World Energy Council and others, and predicts that total energy demand will triple between the years 2000 and 2050, with the total electricity demand rising five-fold.

The graph illustrates well-known limitations on additional hydroelectric power production (about twice the current global capacity before all viable sites have been harnessed). The "new renewables" contribution represents a mammoth commitment to solar, wind, geothermal, and other renewables, but is limited by the availability of suitable sites and the rate of expansion of the resources. Some carbon capture and storage is expected for fossil fuels, but economic considerations provide limitations on the extent of this contribution. Finally, the graph includes a sum of the "low" and "high" nuclear estimates of the capabilities of nations—both those with a current nuclear capacity and those that plan to have nuclear power in the future.[29] The current substantial global interest in and commitment to nuclear power reflects a recognition of the limited options for alternative energy resources. To provide any possibility of reducing the necessity of meeting global electricity needs with conventional fossil fuels, a balanced and substantial contribution from both nuclear and new renewables is needed.

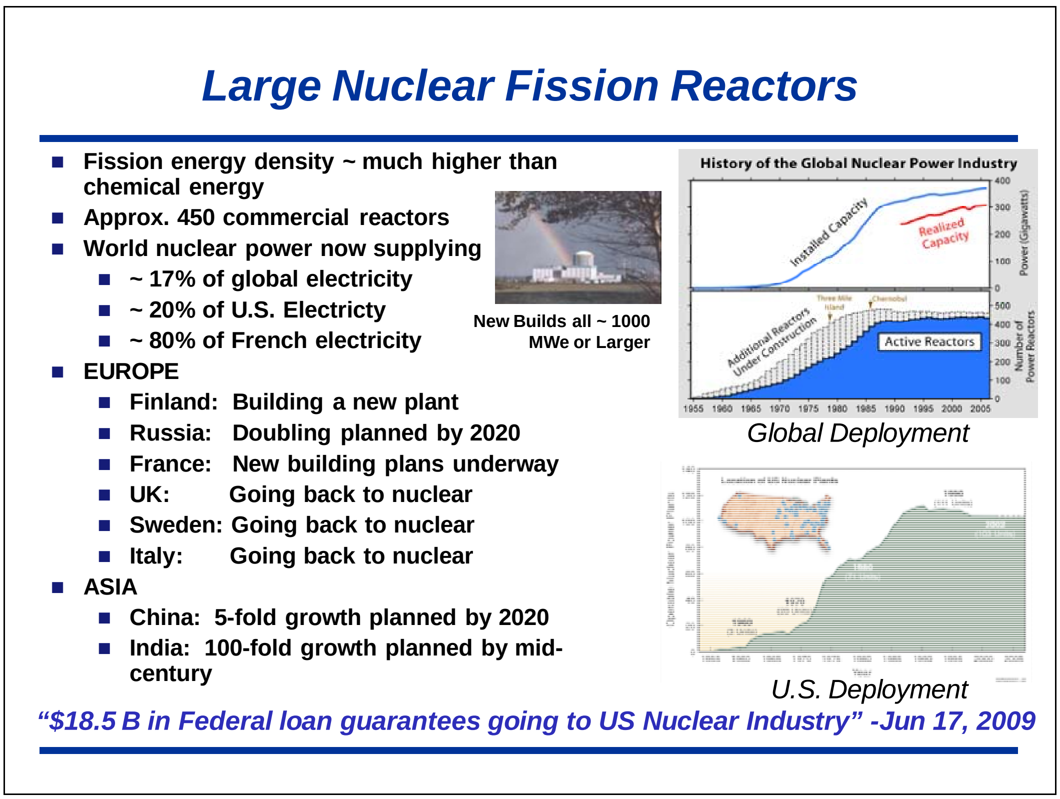


Figure 5-2. Summary of the Panel's Findings Regarding Large Nuclear Reactors.

From an Air Force perspective, nuclear power offers considerable economic and operational benefits. Nuclear reactors emit no carbon oxides during operation, nor any other atmospheric pollutants. With carbon taxation of some sort a near certainty in the future, the

29 The projection of a portfolio of energy resources was conducted by the World Nuclear Association in consultation with a large number of representative nations, who provided a range of their high and low estimates for the amount of nuclear power expected to be installed in their nation in the coming decades.

economic advantage of nuclear power will further improve. Whereas high capital costs are a major hurdle for new nuclear plant construction, the introduction of small nuclear plants (suitably sized for Air Force bases) offers the potential to allow factory fabrication and advanced manufacturing technologies to reduce the up-front costs significantly.[30] Assuming nuclear fuel will be recycled (as is done currently in France and Japan) nuclear energy can provide a large fraction of the world's electrical power needs for many hundreds of years. Thus, nuclear power provides a hedge in pricing relative to energy sources relying on natural resource materials of diminishing supply.

Furthermore, nuclear power has convincingly demonstrated its reliability 24/7/365, offering attractive operational advantages without the need for electricity storage. Nuclear fuel exhibits very high energy density, which results in a reactor system with a small footprint and small land requirement. This land footprint increases when regulators restrict activities within a certain distance of a plant. But such restrictions are less onerous with the smaller reactor designs relevant to this Study.

Therefore, nuclear power, along with new renewables, offers considerable operational and economic benefits to the Air Force. Nuclear and new renewables could form a complementary package to provide the Air Force with a clean, sustainable source of electrical energy free from the existing electrical, oil, and natural gas commercial grids.

5.2 The Move to Smaller (100 MWe) Nuclear Reactors

The first half-century of nuclear power development resulted in over 100 large nuclear power plants in the United States and approximately 450 reactors in 30 other nations, producing approximately 17% of global electricity. Most of the facilities are in the 1,000 MWe or higher capacity range. A current trend in the industry is the development of smaller, 100 MWe-class modular reactors. This trend is motivated by the reduced capital outlays required for smaller reactors. Furthermore, smaller, modular plants take advantage of current manufacturing capabilities that are sized for making much smaller reactor vessels. More factory fabrication (rather than on-site construction) is expected to further reduce costs. Smaller plants also allow siting closer to the energy demands, greatly reducing the need to install expensive transmission capability and allowing utility companies to add capacity in an optimal manner to meet new load demands.

Such factors have led to substantial innovation in the design of deliberately small nuclear power plants for commercial use.[31] The International Atomic Energy Agency lists over 50 active design efforts, coming from many nations, to meet the growing need for such power reactors.[32] The security and safety features being incorporated into some of the new small reactor systems are of particular interest for potential Air Force base siting:

- Hardened, underground placement of the reactor itself
- Fuel designed for longer periods between change
- Enhanced passive controls and inherent safety features

30 Nuclear Energy Institute, 2009.
31 Ingersoll, 2009.
32 International Atomic Energy Agency, 2005.

Such parameters make siting on a military base a tenable possibility from the perspective of the base. From the perspective of the power providers, the security of locating such assets "behind the fence" on a military base is attractive.

The three primary coolants being considered for the smaller reactors are water (the mainstay for the large commercial power reactors of today), gas (helium or carbon dioxide), and liquid metal (sodium or lead). Several of these designs—backed up by decades of relevant R&D and actual operating experience—are in the size range of applicability to Air Force bases. However, several challenges remain prior to their actual adoption, construction, and operation.

Perhaps the major challenge of the new smaller plants is that of licensing from the NRC. In current practice, the NRC will not devote the resources needed to license a reactor unless a domestic customer is ready to proceed with siting and building the reactor. Despite growing interest, no domestic customer has placed a firm order for a small reactor. Therefore, the NRC has not commenced the process of licensing small reactors. This represents an opportunity for the Air Force to host a pilot demonstration, following the example of alternative energy installations at Nellis and Tinker AFBs. As with those energy projects, the Air Force base would be the host, but the investment, construction, and operation of the power source would fall to the utility or private partner.

Like all thermal energy systems, a heat sink must be available for operation of a small nuclear reactor. Most fossil fuel and nuclear plants operating today use a nearby river or other large body of water as a heat sink. For a small 100 MWe power plant, most sites can meet the cooling requirements[33] since it may even be possible at some sites to provide the required cooling with air-blast heat exchangers, often called "dry cooling."

The other major factors requiring attention for siting a nuclear plant on a military site are the disposition of the used nuclear fuel and political and societal acceptance. One of the least publicly understood aspects of the nuclear fuel cycle is that the ultimate nuclear waste is of very small volume compared to energy generated, a volume logistically and technically easy to handle.

For a nuclear plant sized at 100 MWe, a size compatible with Air Force or Joint bases, the mass of high level nuclear waste generated per year would be approximately 200 pounds, about half the size of an office filing cabinet. The scale factor of 2 pounds of high-level waste per MWe of electricity generation per year is similar for larger power plants. The recent decision to halt the Yucca Mountain nuclear geological repository effort is seen by nuclear critics as the reason to stop any further nuclear power development. However, over 95% of the materials residing in the fuel removed from power reactors contains Uranium-238, an element that can be recycled into new fuel elements. The remaining 5% contains useable fissile fuel (Uranium-235 and Plutonium-239) that is a valuable commodity for inclusion in new fuel elements. There are also radioisotopes that have considerable value in the commercial market for industrial and medical applications.[34] It has been demonstrated for many decades that used nuclear fuel can be stored safety in above ground storage units awaiting recycling. Storage of the used material within the confines of a military base would reduce its vulnerability to a terrorist threat.

33 See Appendix A.9: Small Fission Reactors.
34 Waltar, 2004.

Public opinion remains another significant concern. Improvements in operational performance of the current commercial nuclear power plants since the Three Mile Island and the Chernobyl incidents has resulted in improvements in public perception of nuclear power, as indicated by opinion polls. Polling indicates approximately 70% of the American public supports nuclear power,[35] most likely due to a combination of the long-term safety and reliability record of commercial nuclear power plants and the growing recognition among the public of the environmental, economic, and national security costs and risks associated with fossil fuel-based energy plants.

Nuclear power represents a large-scale, carbon-free energy source capable of supplying the long-term electricity demands of the planet. Nuclear power can, in principle, be located at any geographic location that has modest cooling capability.

The siting of a small nuclear reactor on an Air Force installation brings the following benefits:

- The reactor owner/operator takes advantage of the government land, infrastructure, and security already in place on the base (reducing start-up costs). The owner/operator sells power to the base with the excess going onto the commercial grid, and, by virtue of exporting power to the grid, qualifies for an NRC review and certification of the small plant design (thereby allowing the smaller design to be replicated and sold world-wide).
- The base gets assurance of full access to a reliable source of electricity, even in the event of commercial grid failure, and obtains a contract for electricity at a competitive, negotiated price; this satisfies the Air Force's goals of energy surety, economic savings, and reduced carbon footprint.
- In leading on this issue, the Air Force would provide national leadership in developing a new, small energy system of profound value for multiple sitings in relatively remote areas of the United States and around the world.

Since the NRC review and certification process would likely require a minimum of four years, small nuclear plants are not a near-term solution, but could be online within 15 years.

5.3 The Complementary Roles of Small Nuclear and Renewable Power Sources

Ensuring a continuous, available supply of electrical energy is critical to many Air Force operations, especially for command and control, logistics, maintenance and other missions where a power outage of many weeks or repeated power disruptions would have particularly adverse consequences.

The Panel's review of the strengths and weaknesses of renewables and nuclear energy shows that no universal solution exists to address the energy security issue for all sites. At those installations where renewables are feasible to implement, a renewable solution may be the best option when combined with effective storage systems. For other bases, nuclear may be the only feasible option. From a systems standpoint, renewable energy sources and nuclear power are complementary parts of the solution to secure, clean power. A nuclear system complements the intermittent nature of renewables without need of storage. During reactor shutdowns, due either

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35 Bisconti, 2008.

to refueling or a malfunction, complete reliability can be attained only through direct ties with the local electrical grid—a systems approach, as recommended elsewhere.

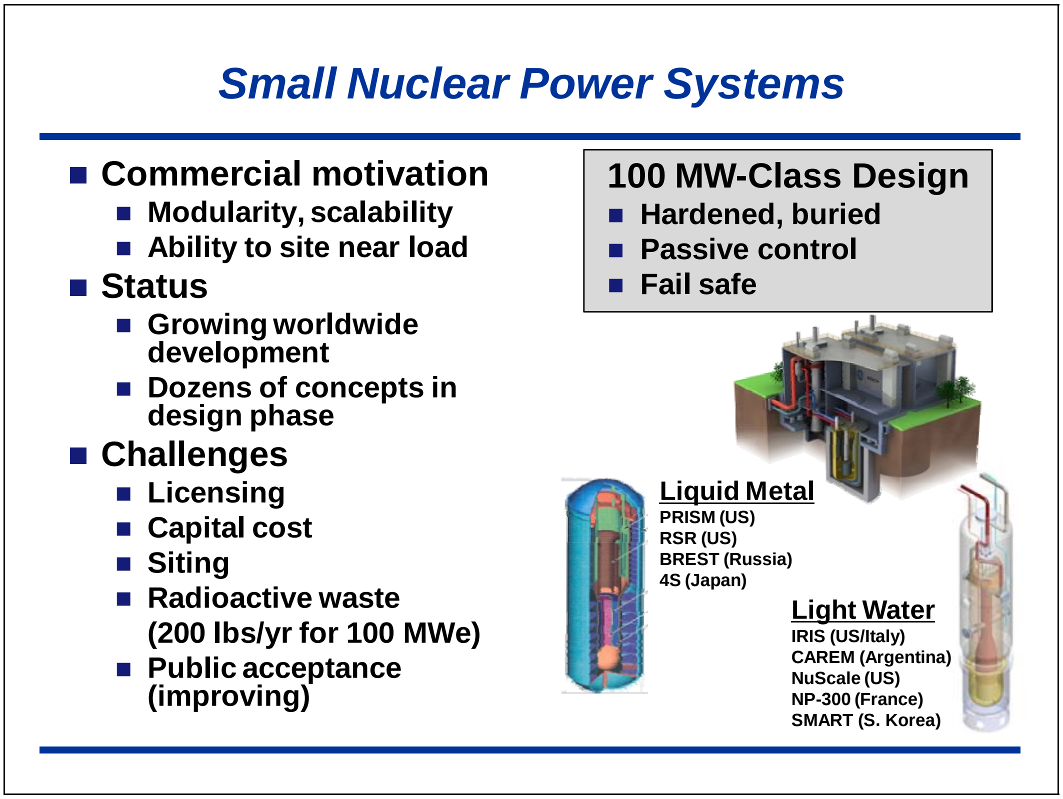

Figure 5-3. The Development of Small Nuclear Power Systems Brings a Reduction in Startup Costs, Land Footprint, and Waste Materials to be Disposed.

Given the intrinsically low power intensity of sunlight and wind, the collection area for a reasonably sized alternative power generating plant is relatively large. In contrast, a 100 MWe nuclear plant occupies a relatively small area of land due to the exceptionally high power density of nuclear fuel. Although a significant controlled zone around the reactor is normally required by the NRC,[36] the exceptionally strong passive safety features and lower output of the small nuclear plants opens the possibility for significantly reduced controlled zones.

Most of the small nuclear plant designs under consideration feature an underground location for the reactor itself, further reducing vulnerability to attack. An attack might disable the power conversion portion of the plant (residing on the ground surface) and result in the loss of power. Although the consequence of a power loss would be similar to that of an attack on a renewable plant, an attack on a base containing a nuclear power reactor could be expected to generate considerable public concern, even if no actual damage or health effects resulted. Since the actual consequences and perceived consequences could differ, bases with small nuclear reactors represent a public affairs challenge.

36 The current NRC requirement for the emergency planning zone is 10 miles for any reactor exceeding 250 MWt (10CFR50.47 (c)(2)).

Public acceptance would be a key to the success of building and siting new small nuclear power plants. Given the increase in favorable support for nuclear power in general, support for the smaller plants may strengthen as the intrinsic passive safety features associated with the small reactor designs become apparent. Furthermore, it would be reasonable to expect the public view the reactors' siting on military bases positively, given the growing security concerns of publicly accessible energy assets. The degree of public acceptance by the community surrounding the base will undoubtedly depend in part on the specific geography of the base and plant site.

Both the Army and the Navy have considerable experience with small reactors, but such reactors were designed for propulsion and other specific applications, rather than the type of service needed to power base operations. Most of the Army reactors were limited to about 2 MWe and almost all were shut down in the 1960s and 1970s. Scores of Naval reactors have been built and deployed to power submarines and aircraft carriers around the world. Although they are appropriately sized for potential base power, their fuel is of substantially higher enrichment than commercial power reactors.

The United States has significant experience with large nuclear power systems, but there are as yet no small nuclear power reactors available for cost-effective power production implementation. As the Air Force aims toward an energy-secure, carbon-limited future for bases, the Air Force should consider taking a leadership role in the use of the new generation of small nuclear reactors.

5.4 Recommendation 4: Make Nuclear Energy Part of Air Force Energy Planning

Although small nuclear plant designs are not currently available with NRC approved licenses, the potential of such energy sources is sufficiently attractive (high reliability, no carbon footprint, no electricity storage required) that they deserve special scrutiny for meeting the Air Force's long-term need for secure energy and environmental stewardship.

Therefore, a near term effort should be focused on the identifying the bases on which a small nuclear plant would be most beneficial to the Air Force. Factors such as the consequences of a long-term outage, current costs of electricity, overall site suitability, and the lack of suitable solar, wind, or geothermal resources should be the major considerations.

A technical evaluation by a team of Air Force specialists, augmented by an appropriate group of experts from the DoE and elsewhere, should determine the best small reactor candidate for siting on an Air Force base. The analysis should consider the potential for partnerships with the other services, with DoE and other government agencies, and with industry and investors. At the appropriate point of technical evaluation, siting analysis, and development of partnerships, the Air Force should proceed to develop a business case in conjunction with the appropriate partners for the most promising concept(s) and identify the path for mid-term siting on the selected bases.

Recommendation (4)

Make nuclear energy part of Air Force energy planning for the future

- **Evaluate a nuclear power generation option for selected bases [OPR: SAF/IE, AF/A7]**
  - **Identify bases that provide the greatest benefit for implementation, considering:**
    - **Consequences of long-term outage**
    - **Local power costs**
    - **Lack of suitable alternative energy**
    - **Site suitability/risk assessment**
  - **Perform technical evaluation**
    - **Evaluate current capability of technology base for producing appropriate facilities and operational implications on the Air Force**
    - **Consider sizing to provide power to the local community**
    - **Consider synergy with DoD/DOE partnerships**
  - **Engage OSD/Services/DOE/Industry for a concept demonstration**
- **Implement best solution for selected bases [OPR: AF/A7]**

Figure 5-4. Summary of Recommendation 4.

Appendix A: Alternative Energy Source Technologies

Relevant to Recommendations 1&4

A.1 Energy Source Technologies

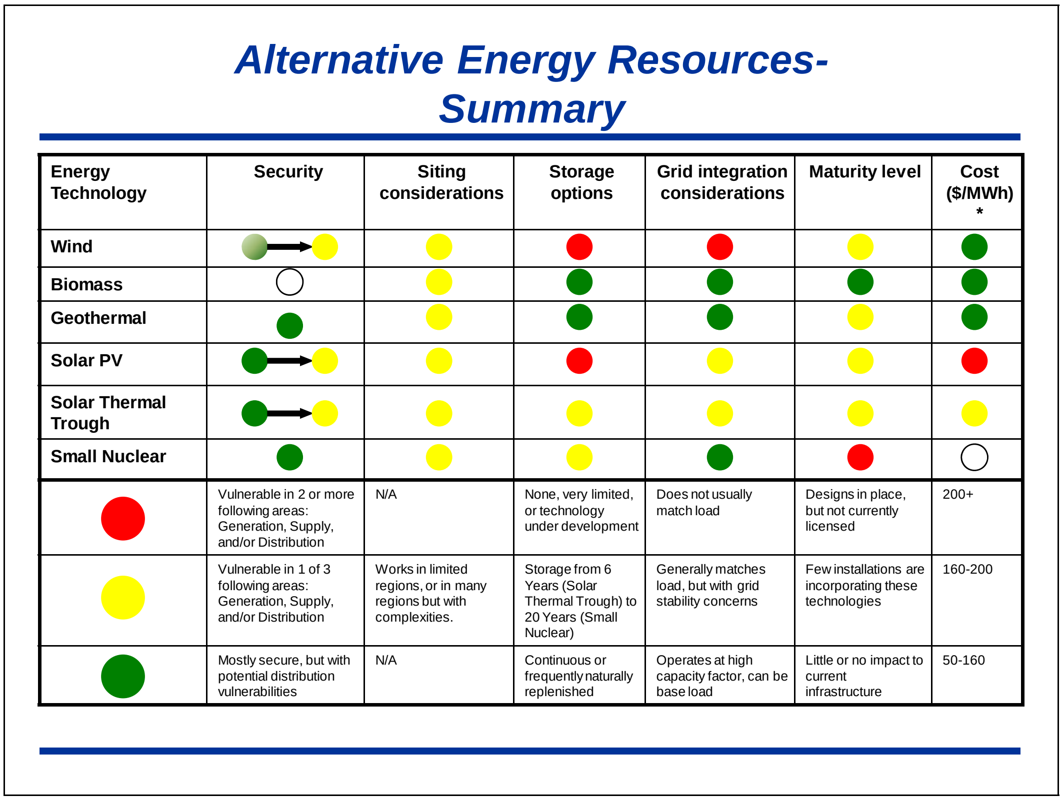

Figure A-1. A Summary of Capabilities and Metrics for Alternative Energy Resources Relevant to Air Force Facilities.

Alternative Energy Source Technologies include most of the technologies that would be examined for potential application to United States Air Force (USAF) bases, both CONUS (Continental United States) and OCONUS (Outside Continental United States). There are a remarkable number of alternative energy source technologies that might be applicable to the USAF at one or more bases, which leads to one of the main recommendations of the Study—that the USAF perform system level trades in order to determine what alternative energy sources should be pursued for a particular base. This Appendix presents the majority of the technologies that might be relevant to USAF bases and includes a summary of the operating principles behind each. The capabilities, potential payoffs, concerns, and future outlook associated with these technologies are discussed, relevant to the current and projected Air Force base energy needs. A high level assessment of the capabilities of these alternative energy concepts is provided in Figure A-1 above. Similarly, a summary of the estimated costs for installation of these

alternative energy concepts is provided as a basis for evaluating the capabilities versus cost for each option in Figure A-2 below.

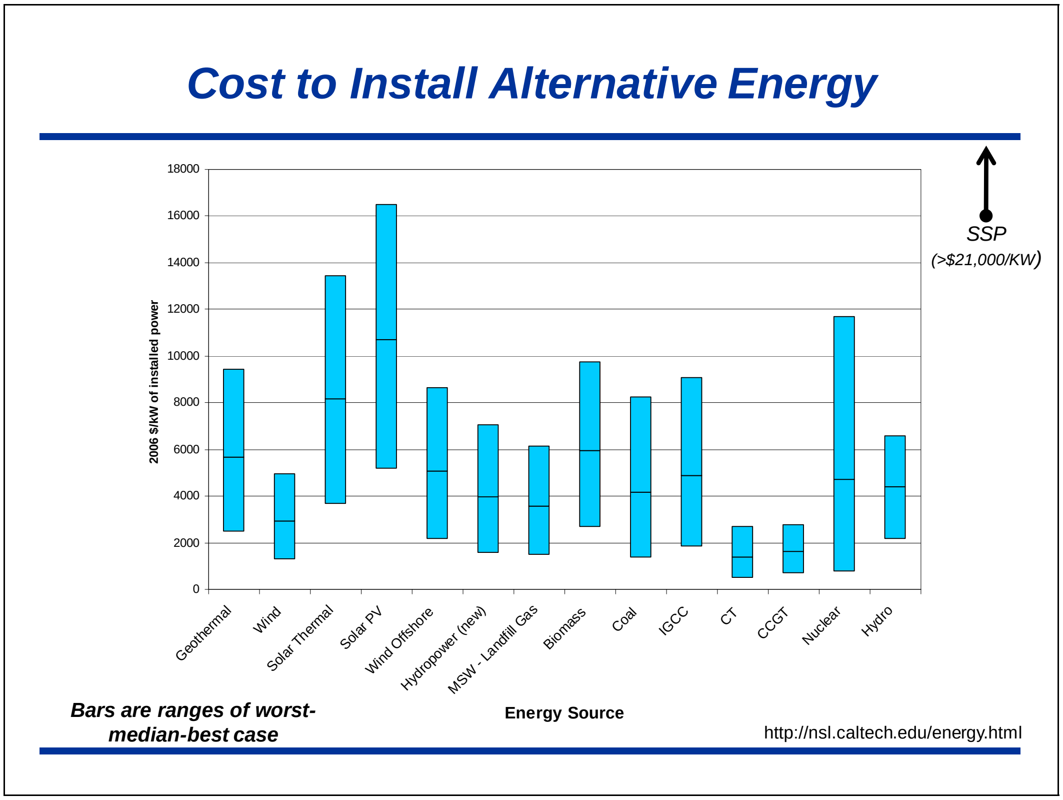

Figure A-2. Summary of Installation Costs for Alternative Energy Systems.

Figure A-2 above presents a number of alternative energy systems as follows:

- PV = photovoltaic, the direct conversion of sunlight into electricity; MSW = Municipal Solid Waste.
- IGCC = Integrated Gasification Combined Cycle, a technology that turns coal into synthesis gas ($CO + H_2$) and then removes impurities from the coal gas before it is combusted, resulting in lower emissions of sulfur dioxide, particulates and mercury.
- CT = Combustion turbine (from natural gas).
- CCGT = combined cycle gas turbine, where a gas turbine generator generates electricity and the waste heat is used to make steam to generate additional electricity via a steam turbine. Most new gas power plants in North America and Europe are of this type.
- SSP = Space-Based Solar Power, photovoltaic panels in geostationary earth orbit generate electricity, which is beamed to earth in the form of near infrared laser or microwave radiation.
- Because it can be found in abundance in America and because its price has remained relatively constant in recent years, coal is used for about 50 percent of US electricity needs.

With regard to energy storage technologies and power management (and additional considerations for USAF expeditionary bases the Panel identified a number of available energy storage systems that are required for bridging intermittent sources, providing power for individual functions on base, or providing power for extended periods of time to allow bases to continue to carry out their missions in the face of long duration commercial grid outages. Again, these technologies are presented as a summary of the technology, the basic physical or chemical principles under which the technology operates, the capabilities and potential payoffs, and the concerns and issues that might restrict the use of the technology by the Air Force.

Following the description of energy storage options, the micro-grid elements are described in the context pertaining to USAF base utilization. Capabilities and benefits, concerns and issues are also described for these micro-grid technologies.

Finally, a group of energy technologies associated with expeditionary bases are described in more detail. Again, a summary of each technology, its basic principles of operation, its capabilities and benefits, concerns and issues are all described. At the end of each technical description a list of references and in some cases an additional bibliography is given. The following technologies are explored in this Appendix:

- Geothermal
- Wind
- Solar
  - Solar Photovoltaic (crystalline)
  - Solar Photovoltaic (thin film)
  - Solar Thermal
  - "Sunshine to Petrol" (S2P Project, Sandia National Laboratories)
  - Space-Based Solar (SSP)
- Nuclear
  - Small Fission
  - Large Fission
  - Fusion
- Ocean/Wave
- Biofuels
- Novel Processed Fuels
- Biomass
- Waste to Energy
- Landfill Gas
- Hydroelectric
- Energy Conservation

A.2 Geothermal Energy

A.2.1 Summary

Geothermal energy is created by harnessing the heat generated by local geothermal activity in the earth. There is a debate over whether or not geothermal energy is technically a renewable energy source, as a local geological “hot-spot” can cool down with time. Likewise, there is widespread debate as to its effectiveness for electricity generation or heating. However, there are many examples of cost-effective geothermal energy projects worldwide. Within the Department of Defense (DoD), the US Navy has been given the lead in geothermal energy development—the China Lake Naval Station geothermal facility is one of the largest in the world. Geothermal energy is extracted by setting up a closed system with water or some other fluid as a heat exchange medium. The reason geothermal is generally considered a “green” renewable is because the process does not release carbon dioxide into the atmosphere and the heat source is usually very long-lived. However, substantial amounts of noxious gases (e.g., hydrogen sulfide) are usually associated with geothermal regions, and the process of heat extraction can exacerbate the situation.

Geothermal

- **Uses hot water or steam from the Earth’s core to generate electricity**
- **Operates at a high capacity factor and can be a base loaded resource**
- **Matching fuel source to power plant size is critical for long-term viability**
- **Finding the resource is the most difficult and risky part of developing a geothermal project**
- **May use water for cooling**
- **Little or zero emissions**
- **$57-$150/MWh**

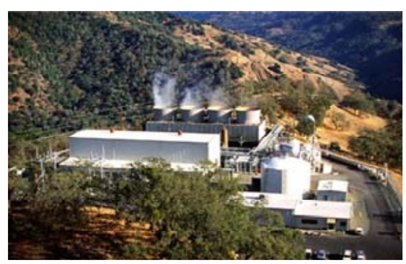

Figure A-3. Summary of Geothermal Energy Source Benefits and Concerns.

A.2.2 Operational Principle

Geothermal energy involves digging wells to extract thermal energy from hot rock or magma in those regions of the world where the magma is close enough to the surface of the earth to make the drilling of wells feasible. Water is injected into pipes located in the wells, pumped down into the surrounding hot rock where it is turned into steam. It then returns to the surface

where it spins turbines to generate electricity. This is a closed-loop system, but significant quantities of water are usually needed for makeup purposes.

A.2.3 Capabilities and Payoffs

Technology	Geothermal
Attributes	Little or no emissions; requires cooling water
Site Considerations	Resource location is most risky and difficult part of a project
Storage Options	Can be operated base load, must match plant size with resource size for viability
Grid Integration Considerations	Operates at high capacity factor, can be base load
Maturity Level	Decades of experience at California installation; deep drilling requires more advancement; some risk in location and identification of resource
Cost ($/MWh)	57-150

Table A-1. Capabilities and Payoffs of Geothermal Energy Sources.

In regions of high resource, the hot rock generally maintains a constant temperature, and so geothermal operations are 24/7 and highly reliable (except for the need to replace piping and rotating equipment on a regular basis as a result of the corrosive environments). Since the energy source is always available and essentially free, it is most cost-effective to run geothermal plants on a high capacity, base load basis.

Geothermal energy has the distinct advantage (along with nuclear) of not requiring energy storage. These systems can operate at full power on a continuous basis.

A.2.4 Concerns and Issues

The largest impediment to harnessing geothermal energy is the lack of good sites. The best CONUS regions for development are in the western United States (Figure A-4 below), generally, encompassing the mountain ranges. This necessarily means that the sites are normally located at considerable distances from the load centers.

Decades of experience have been accumulated for geothermal plants in California and in other parts of the world (e.g., New Zealand). However, the deep drilling technology required to access and develop many new sites forms a significant barrier to large-scale deployment. Deeper resources require more extensive drilling to locate and exploit, driving up costs.

The cost of geothermal energy is generally in the higher range of energy alternatives, but this is countered by the advantage of continuous operation without storage.

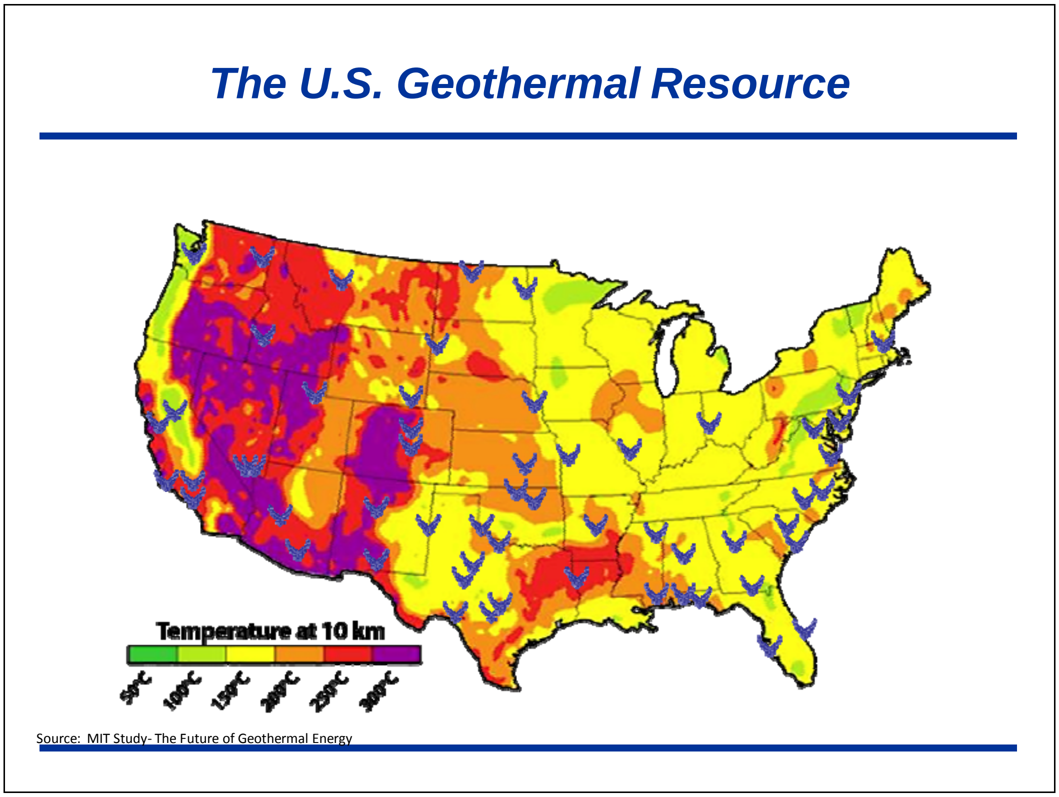

Figure A-4. Relationship of USAF Bases to Geothermal Energy Resources. (The economic viability of a geothermal plant is highly dependent on the temperature of the resource; the typical cutoff to generate high pressure steam is 180° Centigrade.)

A.3 Wind Energy

A.3.1 Summary

Wind, the motion of the air, is caused by uneven heating of the earth. This motion represents a significant potential source of renewable energy. The harvesting of wind power is becoming increasingly popular around the world. In 2007, worldwide installed wind capacity was 94 gigawatts (GW), with 17 GW in the United States alone.[37]

A.3.2 Basic Principles

A wind turbine converts the kinetic energy of the wind to electric energy through the turning of a rotor and generator to produce electric current. This current is direct current and must be inverted to create an alternating current before being fed to the grid. As of 2008, a typical modern wind turbine stood 60-80 m (meters) off the ground with rotor diameters of 70-80 meters in a three rotor configuration. A single wind turbine of this size can generate around 1.5 megawatts (MW) of power.[38] Typically, these turbines are deployed in giant "wind farms" with many turbines sited at a given location. Because the prevailing winds tend to increase with

37 United States Department of Energy: Annual Report on US Wind Power, 2007.
38 United States Department of Energy: 20% Wind Energy by 2030, 2008.

increasing distance from the ground, wind turbines continue to increase in height and size as the technology to produce the giant rotor blades advances. For example, General Electric's primary wind turbine has increased in rotor size from 70 m in 2002 to 83 m in 2008. The average power of a single wind turbine has grown from 0.7 MW in 1999 to 1.65 MW in 2008.[39]

Wind

- **Variable production over course of day**
- **Timing of wind energy generally not coincident with load**
- **Zero emissions**
- **Research being conducted to couple wind energy with compressed air energy storage (CAES) for base loaded, dispatchable resource**
- **$65-$120/MWh**

Figure A-5. Summary Information Concerning Wind Energy Resources.

While they represent a large source of renewable energy, there are a number of considerations in assessing the true potential and utility of wind energy. The average wind speed and the probability of having significant wind vary dramatically from location to location. Even at a good location for wind, the amount of wind will vary considerably over the course of a day, with both a strong diurnal pattern as well as a large random component. Finally, wind turbines have important impacts on radar systems with line of sight or even beyond line of sight to the turbine, if the radar is at a frequency which can propagate beyond line of sight. All of these factors impact the feasibility of deploying and using wind power in specific locations and as part of the overall electrical grid. The specific concerns involving the impacts on wind and other renewable energy projects on USAF radar systems and test ranges are treated in separate Air Force Scientific Advisory Board studies (FY 2009 and FY 2010).

39 General Electric Energy, 2008.

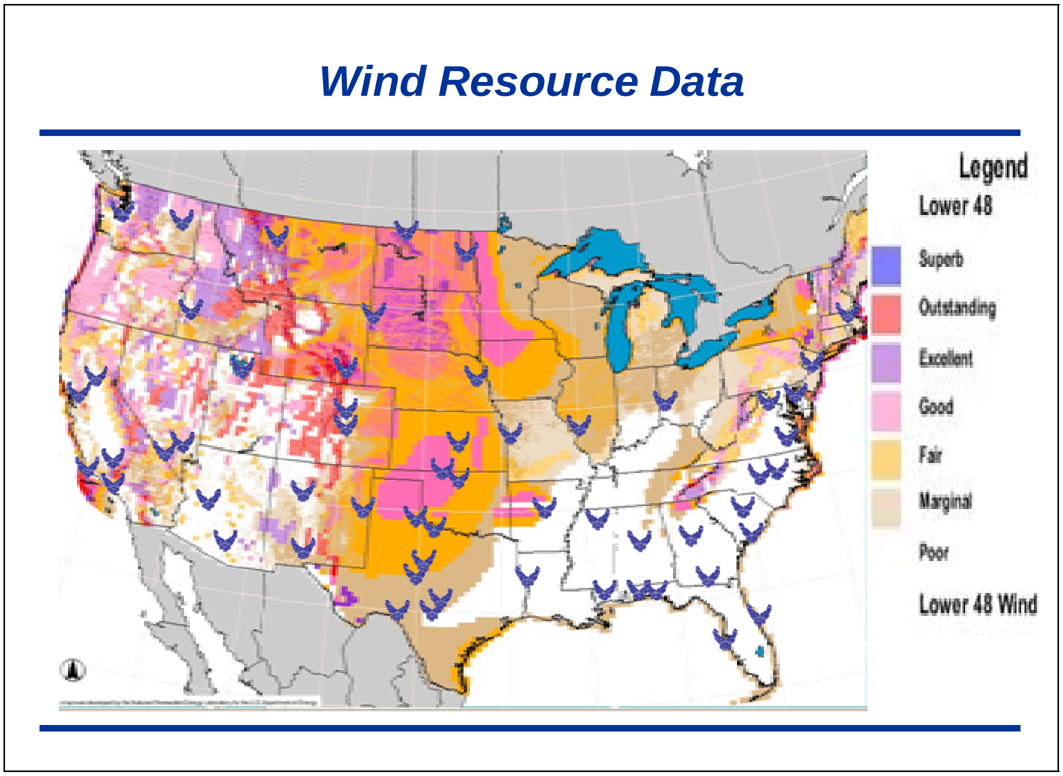

Figure A-6. Relationship of USAF Bases to Wind Energy Resources.

A.3.3 Capabilities and Payoffs

A.3.3.1 Siting Considerations

As mentioned above, the availability of significant amounts of wind energy is very location dependent. For example, Figure A-6 above shows the average wind speed at an altitude of 50 meters for the entire United States, with darker colors indicating higher average wind speeds. The rated windspeed for the General Electric 1.5 MW turbine is 11-14 meters per second (m/s) and the cut-out speed is 3.5 m/s. Therefore, areas in the lightest color of the map are not appropriate for wind energy deployments of this scale at the current level of the technology.

The wind resource is considerably variable even on a scale of a few miles, as highlighted by the 50 m altitude wind speed map for Missouri shown in Figure A-7 below. Therefore, before developing a wind project, it is very important to investigate the available wind energy at that specific location. Wind resource assessments for a specific site usually need to be performed for a period of at least one year.[40]

A.3.3.2 Grid Integration

A key factor for integrating wind energy into the electrical grid is the variability of the wind itself; the power output of a wind turbine will track the wind speed. Aggregation of a large number of wind turbines can reduce this variability. For example, increasing aggregation from

40 Canadian Wind Energy Association, 2007.

14 turbines to over 250 turbines can decrease the average 1-second variability from 0.4% to 0.1% and over a 10 minute interval from 3.1% to 1.5%.[41] Even with this level of aggregation, electric utility companies prefer to limit penetration of wind energy to less than 20% of their resources, even with whole regional grids available to balance power load variability.

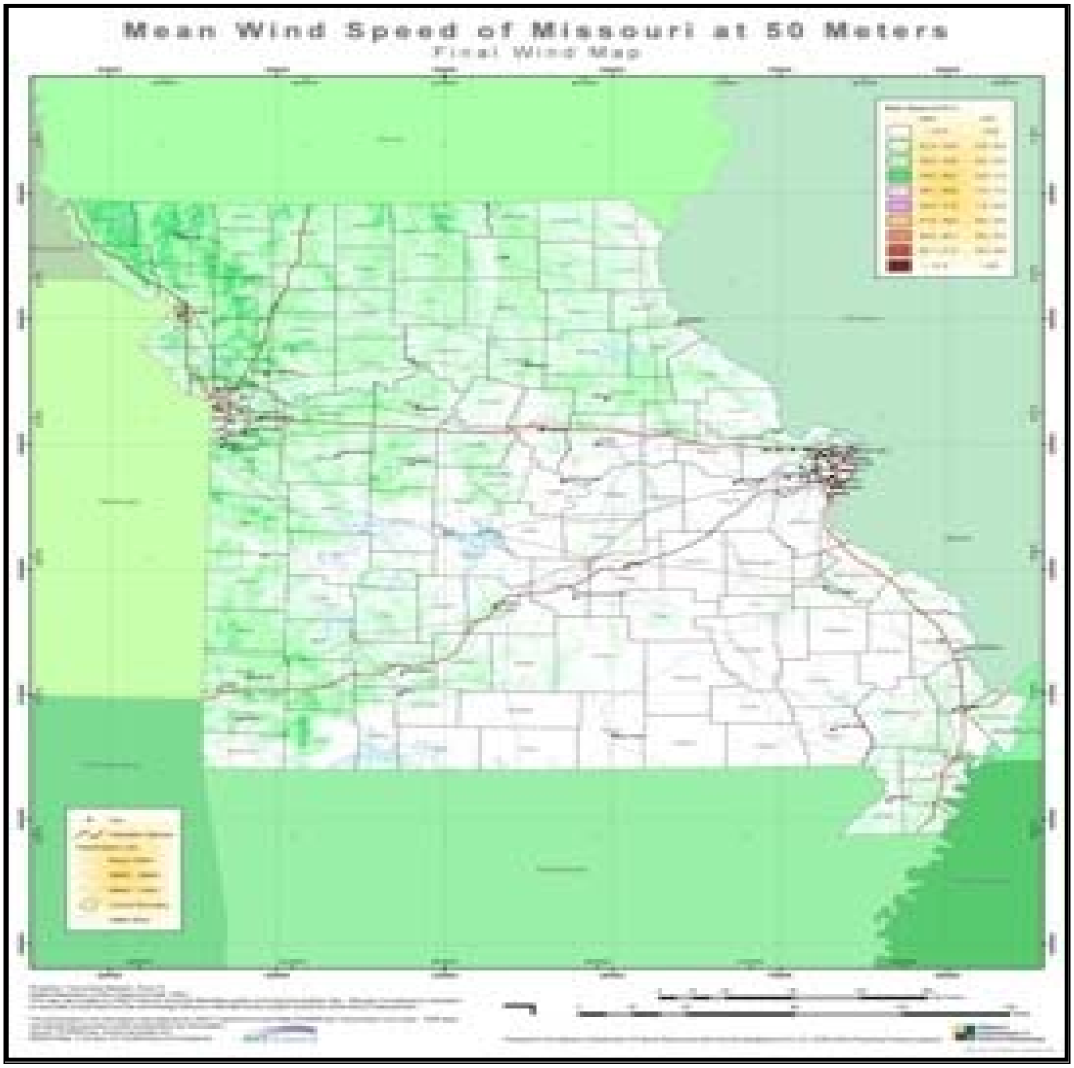

Figure A-7. Average Wind Speed at 50 Meter Altitude in Missouri.

A.3.4 Concerns and Issues

A.3.4.1 Storage

Storage is highly desirable to even out the production of wind-generated power, which adds considerably to the cost of a project. Appendix B provides more information regarding energy storage.

41 United States Department of Energy: 20% Wind Energy by 2030, 2008.

A.3.4.2 Maturity Level

Wind technology is very mature with significant deployments world-wide. The technology continues to slowly advance, with turbines growing in size. Other niche technologies are also in development including small (less than 20 kilowatt (kW)-class) turbines for behind-the-meter type applications and dedicated system concepts for off-shore turbines. These types of systems are available today, although technology maturation is expected to continue to drive down total system cost. For example, two-thirds of the cost of an off-shore wind turbine project goes to installation, with the remaining one-third of the cost going to the turbine generator itself. This contrasts with land installations, where the turbine generator is greater than 50% of the total system cost.[42]

A.3.4.3 Radar Impacts

One factor which has caused significant concern for wind turbine deployment in the United States is the impact of the wind turbines on radar performance. The blades of wind turbines reflect the energy received from a radar, with the magnitude of the reflected energy equal to or even significantly larger than what might be seen from a large commercial airliner. Equivalent radar cross sections of 30-50 decibel square meter (dBsm) have been measured. Unlike a large building or mountains, which may have equivalent radar cross sections, wind turbine blades are moving. Because it is rotating, each part of the turbine blade is moving at a different linear speed, so that the energy returned from the blade will have Doppler shifts varying from that equivalent to the turbine tip speed (~80 m/s), to zero. Even though a speed of 80 m/s is much slower than most aircraft, the radial velocity of an aircraft relative to a given radar can be anywhere from 300 to 0 m/s. Since radars often use Doppler shift to differentiate aircraft from ground clutter, this Doppler spread of the wind turbine return overlaps with the aircraft signatures, and the radar may not be able to distinguish the turbine as ground clutter.

This difficulty in separating wind turbine returns from aircraft leads to a number of problems for the Air Force and the Federal Aviation Administration (FAA). One is that the probability of detecting real aircraft flying over the wind farm may be decreased, either because the required signal to noise threshold for detection has been increased or because the return from the aircraft is buried in the return from the wind turbine. This problem may be seen even at high altitudes depending on the elevation beam width of the radar and the way it processes returns from different elevations. Wind turbines can also lead to a large number of false alarms where the radar reports an aircraft where there is none. This can confuse an operator or cause the generation of false target tracks.

Today in the United States, radar systems are used for a number of different purposes including air traffic control, weather monitoring and prediction, and homeland defense. Wind turbines can interfere with radars performing any of these functions. Because of these problems, a number of processes have been put in place to prevent siting of wind farms in critical locations. These processes have been partially successful, but there is growing degradation of US radar coverage because of wind turbines. At the same time, these processes have led to significant delays, or even failures of specific wind turbine projects.[43]

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42 *Ibid.*
43 Spaven Consulting LLC., 2001.

In January, 2006, Congress passed a law requiring the Defense Department to study the interference that wind turbines present to radar systems. The impact on new wind turbine construction has been significant—wind projects representing over 3,000 MW of power generation are at risk. In 2006/7, more than $1B of project construction was halted, impacting six states, and many other projects were slowed. Given the potential importance of wind power in renewable and clean energy technologies, it is important to consider both mitigation strategies and, if possible, radar-invisible wind generators.

A number of mitigation strategies can be employed which fall into three broad categories:

- Proper placement of wind turbines,
- Wind turbine modifications, and
- Radar modifications.

If possible, wind turbine location is the first line of attack on the problem, but siting of wind turbines cannot be arbitrary, so there is some limit to the use of this option. Look angles can be refined, and the blades can be modified to make them less visible to radar. Other strategies include transponder integration, software modification, additional hardware (including post processors), and adding more transmitters and receivers.

A relatively straightforward mitigation strategy is radar software modification. These include enhanced clutter mapping, concurrent processing, separation of high and low beams, ties to advanced clutter models and geo-based information, improved filtering algorithms, advanced tracking, and adaptive Doppler filtering techniques. Application of some of these techniques has considerably improved several systems.

For the future, the Panel recommends an aggressive effort to improve algorithms on the one hand, and to improve hardware on the other. The latter may involve research and development (R&D) into "stealth" improvements on both blades and towers.

A.3.4.4 Cost

Since the primary cost of producing wind energy is construction and there are no fuel costs, the average cost of wind energy per unit of production depends on a few key assumptions, such as the cost of capital and years of assumed service. The marginal cost of wind energy once a plant is constructed is usually less than 1 cent per kilowatt-hour.[44] Since the cost of capital plays a large part in projected cost, risk (as perceived by investors) will affect projected costs per unit of electricity.

Many potential sites for wind farms are far from demand centers, requiring substantially more money to construct new transmission lines and substations. In some regions this is partly because frequent strong winds themselves have discouraged dense human settlement. The wind which was historically a nuisance is now becoming a valuable resource, but it may be far from large populations.

The commercial viability of wind power also depends on the pricing regime for power producers. Electricity prices are highly regulated worldwide, and in many locations may not reflect the full cost of production, let alone indirect subsidies or negative externalities. Customers may enter into long-term pricing contracts for wind to reduce the risk of future

44 Patel, 2006.

pricing changes, thereby ensuring more stable returns for projects at the development stage. These may take the form of standard offer contracts, whereby the system operator undertakes to purchase power from wind at a fixed price for a certain period (perhaps up to a limit); these prices may be different than purchase prices from other sources, and even incorporate an implicit subsidy.

A.4 Solar Photovoltaic Energy

A.4.1 Summary

Solar Photovoltaic Systems

Semiconductor devices convert sunlight directly to electricity

Thin-film:
Flexible
Light-weight Efficiency <= 9%

Multi-Crystalline Si
Efficiency <=14%

Crystalline Si
Efficiency <=19%
Tracking mount

- **Components: PV modules, tracking or fixed mount, inverter**
- **Crystalline, Multi-Crystalline, or Amorphous (thin-film)**
- **Variety of materials (Si, CdTe, GaAs, CuInSe, etc). Record efficiency (40.2%) combines GaInP, Ge, and GaAs**
- **High Capital Cost ($7,000 to $9,000/kW)**
- **Output varies with intensity of sunlight**
- **Very low operating cost and maintenance requirements**
- **Long-lived: warranties as long as 25 years, which is remarkable for any generator**
- **Scalable: device-level (Watts); building-level (kW); power plant (MW)**
- **$200-$300+/MWh**

Figure A-8. Benefits of Solar Photovoltaic Systems.

Solar photovoltaics (solar cells) produce direct current electricity from light, which can be used to power equipment or to recharge a battery. The first practical application of photovoltaics was to power orbiting satellites and other spacecraft, but today the majority of photovoltaic modules are used for terrestrial power generation. In order to integrate with a grid-connected system, an inverter is required to convert the direct current (DC) to alternating current (AC). Cells require protection from the environment and are usually packaged behind a protective glass sheet. When more power is required than a single cell can deliver, cells are electrically connected in series and parallel combinations to form photovoltaic modules, or solar panels. Modules vary in size, but a typical single module is sufficient to power an emergency telephone; a house or a power plant requires larger arrays of modules.[45]

45 Zweibel, 1990.

A.4.2 Basic Principles

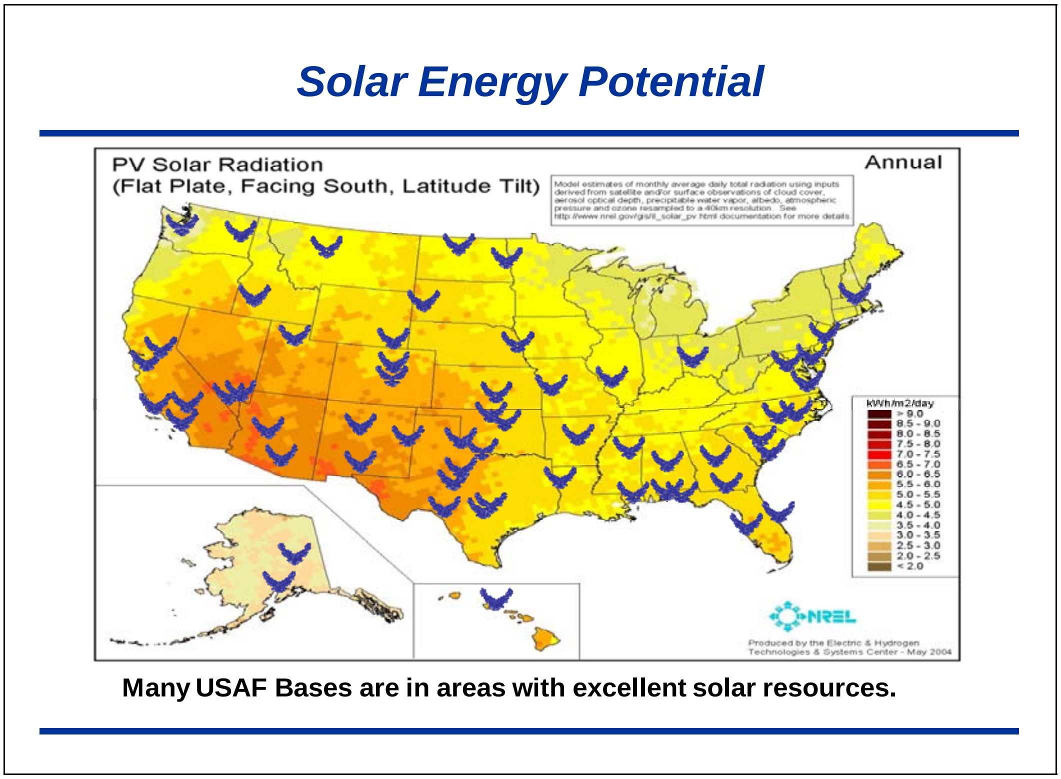

Figure A-9. Solar Energy Potential at US Air Force Bases.

In a photovoltaic solar cell, photons from sunlight excite electrons into a higher energy state; the electrons are collected, routed through an external circuit, and then returned to their ground state in the cell, thereby creating an electric current. The devices have no moving parts and they can last more than 20 years in the field. Virtually all photovoltaic devices use a semiconductor. Silicon is the most common semiconductor used, although gallium arsenide, titanium dioxide, copper indium gallium diselenide, and several other materials are used. Solar cells produce DC which must be converted to AC (using a grid tie inverter) when used in currently existing distribution grids. This incurs an energy loss of 4-12%.[46] Gallium arsenide is a more expensive solar cell material, although its greater efficiency per unit mass led to its use in satellite applications. It has a superior performance at elevated temperatures compared with silicon, and so gallium arsenide (and other semiconductors with energy bandgaps larger than silicon) is preferred in solar concentrator systems, in which a lens is used to gather sunlight and focus it onto the photovoltaic element. The other semiconductor materials under development are of interest because of their potentially lower manufacturing costs relative to silicon.

The solar resource is generally better distributed than the wind resource. Cost and land usage issues aside, any location in CONUS and most OCONUS locations have sufficient solar resources to provide sufficient photovoltaic-derived power for facilities. Figure A-9 (above) provides an overlay of the solar resource with the locations of USAF bases noted.

46 United States Department of Energy: PV Correction Factors, n.d.

A.4.3 Capabilities and Payoffs

The 89 petawatts of sunlight reaching the Earth's surface is plentiful—almost 6,000 times more than the 15 terawatts of average power consumed by humans.[47] Additionally, solar electric generation has the highest power density (global mean of 170 watts per meter-squared (W/m^2) among renewable energies.[48] Solar power is pollution-free during use. Production end wastes and emissions are manageable using existing pollution controls, and end-of-use recycling technologies are under development. Facilities can operate with little maintenance or intervention after initial setup. Solar electric generation is economically superior where grid connection or fuel transport is difficult, costly, or impossible. Examples include satellites, island communities, remote locations, and ocean vessels.

When grid-connected, solar electric generation can displace the highest cost electricity during times of peak demand (in most climatic regions) and reduce grid loading. The grid replaces the need for local battery power in times of darkness and high demand; such application is enabled by net metering. Net metering is a system by which the electricity generated by the local solar or wind resource is fed back into the grid. Time-of-use net metering can be highly favorable, but requires newer electronic controls, and tends to be impractical for small users. Grid-connected solar electricity can be used locally, thus reducing transmission/distribution losses (grid-based electricity transmission losses were approximately 7.2% in 1995).[49] Once the initial capital cost of building a solar power plant has been invested, operating costs are extremely low compared to existing power technologies. Compared to fossil and nuclear energy sources, little research money has been invested in the development of solar cells, so there is much room for improvement. Nevertheless, experimental high efficiency solar cells already have efficiencies of over 40% and efficiencies are rapidly rising while mass production costs are falling.[50]

A.4.4 Concerns and Issues

Although the selling price of modules is still too high to compete with grid electricity in most places, significant financial incentives in Japan and then Germany, Italy, and France triggered a huge growth in demand, followed quickly by production. The photovoltaic (PV) industry is beginning to adopt levelized cost of energy as the unit of cost. For example, the levelized cost of energy of a 10 MW plant in Phoenix, AZ is estimated at \$0.15 to \$0.22 per kilowatt hour (kWh) in 2005.[51]

Depending on the cost of the installation, state and federal incentives, and local electric rates, the payback time for a photovoltaic system can be 14-20 years. While the modules are warranted for 20 years, the investment for an individual consumer is lost if that person moves. The city of Berkeley has come up with an innovative financing method to remove this limitation, by adding a tax assessment that is transferred with the home to pay for the solar panels.[52]

Solar electricity is expensive. Once a PV system is installed it will produce electricity for the same cost until the inverter needs replacing (about 12 years). Current utility rates have

47 Smil, 2006.
48 United States Energy Information Administration, 2008.
49 United States Climate Change Technology Program, 2003.
50 United States Department of Energy, February 2006.
51 National Renewable Energy Laboratory, February 2009.
52 City of Berkely, 2009.

increased every year for the past 20 years and with the increasing pressure on carbon reduction the rates will increase more aggressively.

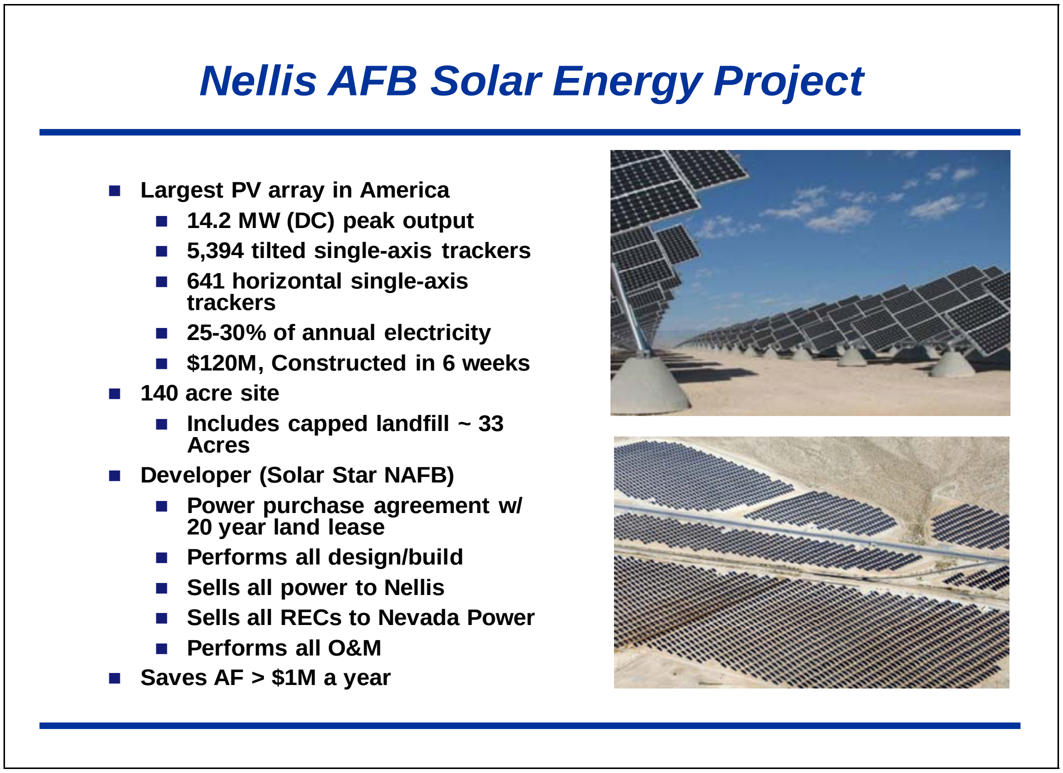

Figure A-10. Nellis AFB Hosts the Largest Photovoltaic Array in the United States.

Solar electricity is not available at night and is less available in cloudy weather conditions from conventional polycrystalline or crystalline silicon-based technologies. Therefore, a storage or complementary power system is required. However, the use of germanium in amorphous silicon-germanium thin film solar cells provides residual power generating capacity at night due to background infrared radiation. Pure amorphous silicon-based solar cells are relatively more efficient in diffuse light conditions than crystalline or polycrystalline cells. However, the amorphous systems have lower efficiency in direct sun than crystalline silicon-based systems.

Another major drawback is the sheer quantity of land required to house a solar power generation plant. For example, the planned 550 MW California plant will require 9.5 square miles of land. Many areas of the country could not find this amount of unused land or assemble the large number of parcels required for this type of project. At the same time, photo-voltaics take up no land at all when installed on existing rooftops or on land not otherwise used, such as decommissioned coal pits or in deserts. The Nellis AFB photovoltaic system (Figure A-10 above) was installed on unusable landfill, for example.

A.5 Flexible Solar Voltaic (Thin Film) Energy

A.5.1 Summary

The previous section focused on photovoltaic cells and systems that are based on rigid materials like crystalline silicon and rigid supports like glass. There is a class of solar cells that are constructed from thin, amorphous, and flexible semiconductors, on flexible supports. The amorphous thin film technology lends itself to a wide variety of applications, including portable power for expeditionary bases. Advantages include flexibility, lower installation cost, increased power output under low light conditions, and a lightweight, easily transported package. Other advantages of flexible solar panels include vandal resistance, durability, and better high-temperature performance than crystalline silicon solar modules.

A.5.2 Basic Principles

Flexible solar cells can be constructed from thin films of amorphous silicon and a few other semiconductors such as titanium dioxide. Specialized conducting polymers are also in development for flexible solar cells. The basic operating principle is the same as with the rigid solar cells discussed above, though there are some unique issues associated with the manufacture of flexible electrical contacts, support structures, and protective coatings. The amorphous thin film technology lends itself to a wide variety of applications, including portable power for expeditionary bases. Advantages include flexibility, lower installation cost, increased power output under low light conditions, and a lightweight, easily transported package. Other advantages of flexible solar panels include vandal resistance, durability, and better high-temperature performance than crystalline silicon solar modules. Commercially available flexible PV has low solar to electricity conversion efficiency of 6-10%.

A.5.3 Capabilities and Payoffs

The attraction of flexible solar cells is that they promise to provide a readily transportable power supply that can reduce the dependence of a deployed or expeditionary base on diesel fueled generators. The costs and risks associated with transporting fuel to forward operating bases is well-recognized,[53] and the Air Force and the other military services (particularly the Army) have an acute need to reduce the amount of fuel used in the field.

The skins or shade cover (fly) of deployed shelters offer one possibility for integration of flexible PV electric power assets. An extensive feasibility project is in place in the “Tent City” on Tyndall Air Force Base. The project focuses on proving commercially available technologies and adapting them to the expeditionary environment. It is a 6-Year research and development program in collaboration with Air Force Research Laboratory’s Airbase Technologies Division (AFRL/RXQ) and the Division’s Deployed Base Systems Branch (AFRL/RXQD); AFRL’s Non-Metallic Materials Division (AFRL/RXB) and its Bio and Nano Technology Branch (AFRL/RXBN); AFRL’s Space Vehicles Directorate (AFRL/RV), and the Air Force Office of Scientific Research. The targeted conversion efficiency for this program is 40%.

53 Defense Science Board, 2008.

Figure A-11. Flexible Photovoltaic Panels are Integrated Into Various Portable Enclosures in the "Tent City" at Tyndall AFB. (This technology demonstrator is used to benchmark the various commercially available technologies and to explore integration options. In some cases, all power to the enclosure (A/C, computers, lighting) is provided by the panels covering the tent exterior.)

A.5.4 Concerns and Issues

The major challenges in the development of flexible PV devices are the needs for efficient light harvesting materials and better approaches for energy collection and conversion. Near-term needs are to use the power produced to offset electricity generated by portable diesel generators. However, solar, wind, and other alternatives offer the possibility to completely replace portable fossil-fuel generators, significantly reducing the logistics tail of the energy system for the expeditionary base. This longer term challenge will require portable, inexpensive, and reliable energy storage systems.

It should be pointed out that micro-grid or related technologies are already successfully deployed in forward operating and expeditionary bases due to the lack of an accessible grid in most areas of interest. These systems can accommodate flexible solar power with minor modifications.

A.5.5 Cost, Maturity, Security

The projected costs of flexible solar power systems are a rapidly moving target. Controlled by constant introduction of new materials and manufacturing technologies, prices are driven by the commercial market and they are dropping due to intense competition. AFRL/RXQ estimates a target price for expeditionary power systems is $7/kWh.

Because the flexible systems do not involve glass, they are more damage resistant and, because they are constructed on a flexible substrate material, they survive impacts and other damaging loads significantly better than the glass-based and other rigid systems. Issues related to security of the power, the inverters and the grid connections are very similar to those of other photovoltaic cell systems.

A.6 Solar Thermal Energy

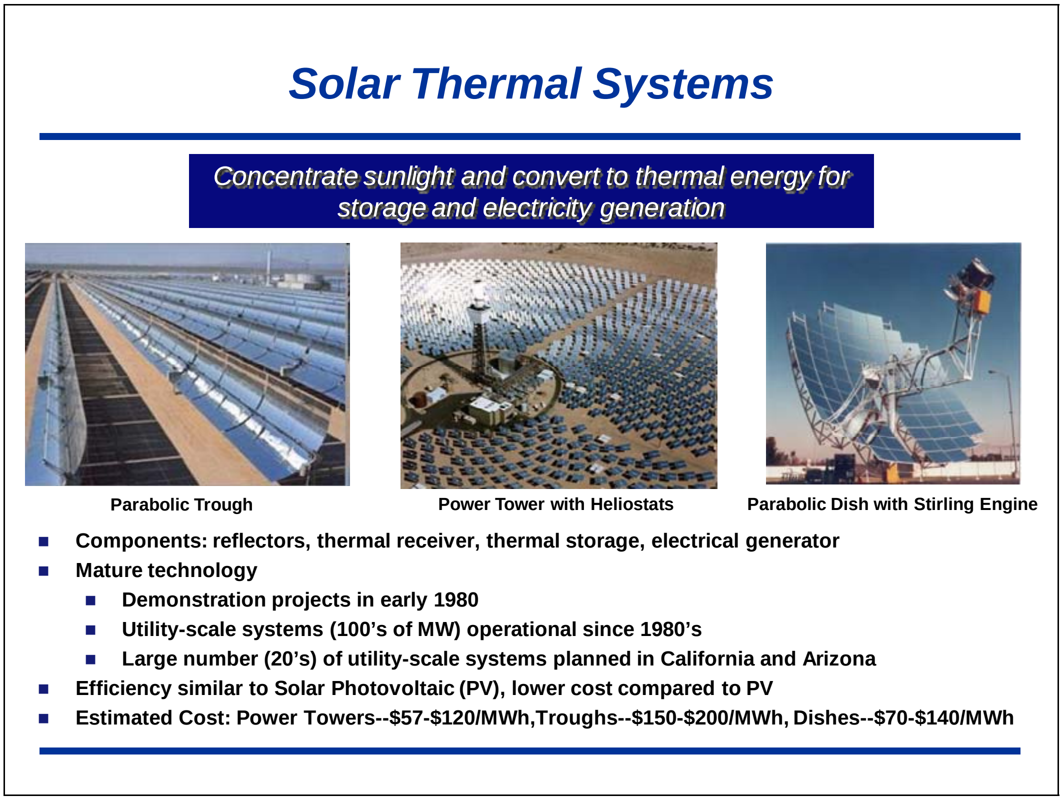

Figure A-12. Three Common Types of Solar Thermal Systems, with Primary Features Listed.

A.6.1 Summary

Solar thermal electricity power systems (also called concentrating solar power, or CSP) harness solar radiation by concentrating sunlight and converting solar power into thermal energy for storage and generation of electricity. The elements of a solar thermal system are similar to a conventional fossil fuel-fired electric generator, except that the heat used to drive the generator comes from focused solar radiation instead of from combustion of a fossil fuel. The basic components of a solar thermal system include:

- Reflectors to concentrate sunlight (e.g., flat mirror, parabolic trough, parabolic dish),
- Thermal receiver for converting sunlight into thermal energy (e.g., bank of tubes with a heat transfer fluid such as molten salt or water),
- Thermal energy storage system; and
- Generator for converting thermal energy into electricity (e.g., conventional turbine generator used to generate electricity from steam).

There are three main types of CSP systems:

- Linear concentrator (also called parabolic trough) which focus sunlight on tubes that run the length of the mirror,

- Parabolic dish with Sterling engine, and
- Power tower system which uses a large number of sun-tracking mirrors known as heliostats to concentrate sunlight onto a receiver on top of a tower.

A.6.2 Basic Principles

A.6.2.1 Solar Parabolic Trough

Solar trough system is the most widely deployed among the solar thermal systems. A solar parabolic trough system utilizes solar irradiance to raise the heat transfer fluid temperature located at the focal line of the trough (the parabolic design maximizes the greatest amount of solar intensity incident upon the focal line for the given surface area of reflective material). The heated fluid is pumped to a heat transfer station where the thermal energy is used to run conventional steam turbines. Rows of troughs are generally configured parallel to geographic lines of longitude with parabolic reflectors capable of an east to west pivot to track the sun throughout the day. The operating temperature of the fluid is generally lower than the solar tower system. Also, the long pipes needed to run heat transfer fluids have correspondingly less thermal mass compared to solar tower systems and thus has less theoretical efficiency.

A.6.2.2 Solar Tower

The fundamental physical principles of the solar tower (solar to thermal conversion) are similar to the parabolic trough system. However heliostats (adjustable reflective panels) focus sunlight on a point rather than a line which requires signature tall towers. Due to large concentration of sunlight, the system typically works at higher temperature and the molten salts with large heat capacity are typically used as heat transfer fluid. The higher temperature heat transfer fluid also has better heat storage characteristics which improve the ability to generate electricity during the night time.

A.6.2.3 Parabolic Dish with Stirling Engine

Unlike solar trough and solar tower systems, the parabolic dish system is very modular which makes it very attractive for lower power systems. A Stirling cycle engine is a device that converts heat energy into mechanical power by alternately compressing and expanding a fixed quantity of air or other gas (the *working fluid*) at different temperatures.[54] In the solar thermal engine, electricity is generated by a conventional generator connected to the rotating flywheel that connects the hot and cold portions of the engine as it is heated using the focused light of the sun through a parabolic mirror.

A.6.3 Capabilities and Payoffs

Solar thermal systems, in particular solar trough systems, are quite mature and very large scale projects are being developed. The cost of solar thermal systems is very favorable compared to solar photovoltaics. Also, due to thermal heat transfer step involved, they have added advantageous characteristics of inherent smoothing of rapid fluctuations in incident sun light and ability to provide a few hours of storage. In addition, solar-thermal conversion can generate steam to be used with existing generators, and the utility/industry has experience with

54 Hoffert, et. al., 2002.

installation and operation of trough systems. Additionally, solar parabolic troughs have efficiency similar to commercial PV arrays ranging from 15% to 20%, but are less efficient than wind turbines that range from 30% to 40%.[55]

By a short-term storage of thermal energy coupled with back-up natural gas power, solar thermal trough systems operate for nearly 100% of peak-usage hours in the Mohave dessert.[56] However, since trough systems use steam turbine generators, other means of energy such as natural gas can be integrated into the system. Techniques for long-term (> 6 hours) storage present challenges, but power towers systems can potentially store thermal energy in large tanks adjacent to towers for longer periods than trough systems.

Power towers can reach significantly higher temperatures than solar parabolic trough systems and can reduce waste heat (in solar parabolic systems, energy loss is high before the heat transfer fluid reaches the heat transfer station due to long and narrow fluid flow paths), however Solar Energy Generation Systems utilizing troughs are a more mature and proven technology than power towers.

The initial expenses of solar trough systems are less than power towers, but long-term costs trends favor power towers. However, the maturity of trough systems combined with more favorable large-scale installation costs explains why parabolic troughs are used in the majority of solar thermal projects listed below in “Solar Thermal System Examples.”

A.6.4 Concerns and Issues

As with any sunlight fed energy production system, cloudy days reduce the power output of the system and so storage must be used to store energy produced during sunny days to be used on cloudy days. For the Stirling engine system this storage can be any of the systems described in the following section. However, for the solar tower and the especially the solar trough, the heating medium is used as the energy storage system in the form of the heated fluid.

Otherwise, the concerns of vulnerability of the system to physical attack are similar to any of the systems that rely on exposed elements in order to perform their task—like PV arrays, sun towers, etc.

A.6.5 Solar Thermal System Examples

A.6.5.1 Example Demonstration Projects: Solar One and Solar Two Power Towers

The 10 MW Solar One plant near Barstow, CA, demonstrated the viability of power towers in 1982. The Solar Two plant was a retrofit of Solar One to demonstrate the advantages of molten salt for heat transfer and thermal storage and was completed operations in April 1999.

A.6.5.2 Example Deployed Systems: Solar Energy Generating Systems (SEGS)

SEGS specifically refers to a solar thermal system that was installed in the Mojave Desert over a period of 16 years. The largest CSP plant in the world, it consists of nine solar power plants in various locations in the Mojave, with a total of 354 MW installed capacity (Table A-2). The installation uses parabolic trough solar thermal technology with natural gas backup to

55 National Renewable Energy Laboratory, 2003.
56 United States Department of Energy, 1998.

generate electricity. Historical cost is about 20 cents per kilowatt hour (kWh), with the current state-of-the-the art system at 11 cents per kWh.

Plant	Year Built	Location	Capacity (MWh)
SEGS I	1984	Daggett	16,500
SEGS II	1985	Daggett	32,500
SEGS III	1986	Kramer Junction	68,555
SEGS IV	1986	Kramer Junction	68,278
SEGS V	1987	Kramer Junction	72,879
SEGS VI	1988	Kramer Junction	67,758
SEGS VII	1988	Kramer Junction	65,048
SEGS VIII	1989	Harper Lake	137,990
SEGS IX	1990	Harper Lake	125,036

Table A-2. Solar Energy Generating Systems (SEGS).

A.6.5.3 Saguaro Solar Trough Power Plant

This 1 MW system is the first solar electric trough system to be built in Arizona and located in Red Rock, Arizona.

A.6.5.4 Nevada Solar One

This is the second largest CSP plant in the world with a nominal capacity of 64 MW and required an investment of $266 million. It is located near Boulder City, Nevada and came online on June 2007. It uses 760 parabolic troughs and covers approximately 300 acres.

A.6.5.5 Solar Tower PS20

The world's largest solar power tower in Seville, Spain has 20 MW capacity and began operating in November 2008. It consists of 1,255 mirrored heliostats, each one 1,291 square feet, and a receiver on top of a 531 feet-high tower, producing steam which is converted into electricity generation by a turbine.

A.6.5.6 Partial List of Large Solar Thermal Projects in the United States

Table A-3 (below) lists some of the large solar thermal projects in California, Arizona, Nevada, New Mexico, and Florida. These projects are in various stages of development.

Project Name	Location	Size	Technology
Victorville 2 Hybrid Power Project	Victorville, CA	50 MW	Solar Trough
Ivanpah Solar	San Bernardino, CA	400 MW	Solar Tower
Carrizo Energy Solar Farm	San Luis Obispo County, CA	177 MW	Compact Linear Fresnel Reflector
Beacon Solar Energy Project	Kern County, CA	250 MW	Solar Trough
SES Solar One Project	San Bernardino, CA	850 MW	Stirling Engine
SES Solar Two Project	Imperial County, CA	750 MW	Stirling Engine
City of Palmdale Hybrid Gas-Solar	Palmdale, CA	62 MW	Solar Trough
San Joaquin Solar 1 & 2	Fresno County, CA	106.8 MW	Solar Trough / Biomass
Mojave / Harper Lake Solar	San Bernardino, CA	250 MW	Solar Trough
Project Genesis	Riverside County, CA	250 MW	Solar Trough
Solar Millennium Ridgecrest	Kern County, CA	242 MW	Solar Trough
Solar Millennium Palen	Kern County, CA	484 MW	Solar Trough
Solar Millennium Blythe	Kern County, CA	968 MW	Solar Trough
eSolar 1	LA County, CA	84 MW	Solar Tower
eSolar 2	LA County, CA	66 MW	Solar Tower
Gaskell Sun Tower	Kern County, CA	105 to 245 MW	Solar Tower
Mojave Solar Park	San Bernardino, CA	553 MW	Solar Trough
Fort Irwin	San Bernardino, CA	500 MW	TBD
Solana Generating Station	Gila Bend, AZ	280 MW	Solar Trough
Mohave Sun Power	Mohave County, AZ	340 MW	Solar Trough
Starwood Solar 1	Maricopa County, AZ	290 MW	Solar Trough
Kingman Solar Project	Mohave County, AZ	200 MW	Solar Trough
Amargosa Solar Power Project	Nye County, NV	250 MW	Solar Trough
Suntower	Doña Ana County, NM	92 MW	Solar Tower
Martin Next Generation Solar Energy Center	Indiantown, FL	75 MW	Solar Trough

Table A-3. Solar Thermal Energy Projects in California, Arizona, Nevada, New Mexico, and Florida.

A.7 "Sunshine to Petrol"

A.7.1 Summary

Using concentrated solar energy to reverse combustion, a research team from Sandia National Laboratories is building a prototype device intended to chemically "reenergize" carbon dioxide (CO_2) into carbon monoxide (CO) using concentrated solar power. The carbon monoxide could then be used to make hydrogen (and then syngas) or serve as a building block to synthesize a liquid combustible fuel, such as methanol or even gasoline, diesel, and jet fuel. Once carbon dioxide is converted to carbon monoxide, the subsequent steps to take carbon monoxide to gaseous or liquid hydrocarbon fuels are established industrial processes.

A.7.2 Basic Principles

The prototype device, called the Counter Rotating Ring Receiver Reactor Recuperator (CR5), breaks a carbon-oxygen bond in carbon dioxide to form carbon monoxide and oxygen in two distinct steps. A catalytic metal oxide in the rotating ring reactor is alternately exposed to concentrated sunlight. This causes the catalyst to undergo periodic heating to a very high temperature. Fresh carbon dioxide is absorbed in the dark "cool" zone, and it is split to carbon monoxide and oxygen in the illuminated "hot" zone. Carbon monoxide and oxygen are released from the hot zone and collected before the catalyst returns to the cool zone to repeat the process. The Sandia research team calls this approach "Sunshine to Petrol." "Liquid Solar Fuel" is the end product—the methanol, gasoline, or other liquid fuel made from hydrogen and carbon monoxide produced using solar energy.

A.7.3 Capabilities and Payoffs

In one example of implementation of this process, coal is burned at a clean coal power plant. The carbon dioxide from the burning of the coal would be captured and reduced to carbon monoxide in the CR5. The carbon monoxide would then be the starting point of making gasoline, jet fuel, methanol, or almost any type of liquid fuel.

The prospect of generating a liquid fuel is significant because it fits in with the current gasoline and oil infrastructure. After the synthesized fuel is made from the carbon monoxide, it could be transported through a pipeline or put in a truck and hauled to a gas station, just like gasoline refined from petroleum is now. Plus it would work in ordinary gasoline and diesel engine vehicles.

While the focus of the current activity is on using sunlight to power the CO_2 to CO conversion, it could be powered by almost any other power source, including nuclear energy.

A.7.4 Concerns and Issues

This technology, though probably 15 to 20 years away from being marketable, holds a real promise of being able to reduce carbon dioxide emissions while preserving options to keep using fuels we know and use so extensively. The infrastructure exists and recycling carbon dioxide into fuels provides an attractive alternative to burying it.

The capability of the system to generate fuel and the potential quantity of fuel produced per hour are still elements to be determined. Currently, the technology is in the proof of concept stage. Besides having a nearly completed prototype, the Sandia research team has already

proven that the chemistry works repeatedly through multiple cycles without losing performance and on a short enough cycle time for a practical device.

In the example given above, where the process is implemented using carbon dioxide exhaust from a coal or other fossil fuel power plant, the combination of the two processes is a net producer of CO_2. However, less CO_2 would be generated per kilowatt of energy than in a coal-burning plant alone. A longer term challenge for the research in this area is to directly harvest CO_2 from the air, to result in a truly net zero carbon footprint. Collection and concentration of the relatively small amount of CO_2 in the air (~400 parts per million) will be a significant challenge.

A.8 Space-Based Solar Power (SSP)

A.8.1 Summary

Developing an economic means of harvesting the abundant energy from of the sun has inspired many concepts; most of them involve terrestrial energy collectors. In the 1970's, the concept of harvesting power from the sun with a space-based platform and wirelessly transmitting it to earth received serious consideration after Peter Glaser first introduced the idea in 1968.[57] A major study led by the Department of Energy resulted in a SSP reference design[58] consisting of a satellite located in a geosynchronous earth orbit with the goal of delivering 5 gigawatts of power. The satellite consisted of a solar array structure that was 10 kilometers (km) by 5 km, with a 1 km antenna to transmit microwave energy to earth. The terrestrial rectifying antenna was 10 km by 13 km, located at 35 degrees latitude. Developing, launching, and deploying a structure of this size presented very significant technical challenges, and was not economically feasible at the time.

A.8.2 Basic Principles

Space-Based Solar Power entails collecting power from the sun with a space-based platform and wirelessly transmitting it to earth either using microwave, millimeter wave, and optical/laser wavelengths. From purely a conceptual perspective, SSP has some appeal since power can be collected continuously in a geosynchronous orbit, can be delivered to remote military operations with terrestrial receivers, can be steered to different terrestrial receiving stations, and can be redirected to meet national emergencies or local energy shortages. However, there are still very significant technology, architectural, and infrastructure hurdles that suggest the SSP concept will not be an economical competitive candidate for alternative base energy unless truly remarkable (i.e., orders of magnitude) advances are made in launch capabilities.

A.8.3 Capabilities and Payoffs

Projected Capabilities are described in Table A-4 below.

57 Hoffert & Potter, 1997, and Hoffert, et. al., 2002.
58 Mankins, 1997.

Technology	Space-based Solar Power
Attributes	Continuously collect solar energy in earth's orbit and transmit power to terrestrial stations via microwaves or low-power lasers. Convert transmitted power to electricity. Zero emissions.
Siting Considerations	Space-based solar satellites are best positioned in a geosynchronous orbit. Terrestrial collectors are very large and range from about 1.0 to 6.5 km diameter.
Storage Options	SSP satellites would be designed to transmit power 24/7. However, there is no inherent storage capability. Compressed air under development; batteries available with limited response time to support grid stability.
Grid Integration considerations	Energy transmitted via a microwave system would be continuous, throughout the day, but transmissions from a laser system would vary with weather conditions (night and day). When weather conditions, are adverse, the laser energy could be transmitted to an alternate site by redirecting the laser beam.
Maturity Level	Very low maturity level. Design concepts developed, but there have been no significant demonstration programs. Requires a capability to launch 1,000s of rockets per year, which is not currently feasible.
Cost ($/MWh)	300-400+ (requires very large initial investment in manufacturing and launch vehicle infrastructure)

Table A-4. Capabilities and Payoffs of Space-Based Solar Power.

A.8.3.1 Siting Considerations

For most concepts, the space-based solar satellite systems are located in a geosynchronous orbit. For those reviewed, the mass of the 1.2 GW microwave system ranged from approximately 15,200 to 29,500 metric tons. The transmitter antennas for microwave systems are of the order of 0.5 km diameter with a terrestrial footprint of 6.5 km diameter. An example laser design consisted of a modular constellation of 480 satellites with a total mass of 14,300 metric tons, and a 1 km diameter solar collector at the ground site.

A.8.3.2 Storage Options

There are no inherent storage capabilities with SSP, but some of the concepts allow power to be transmitted 24/7/365. An SSP microwave system in a geosynchronous orbit, in concept, should be able to provide continuous power. However, an SSP laser system cannot transmit power through clouds, thus a complementary storage system would be required. The storage options would be similar to those considered for other systems, such as batteries.

A.8.3.3 Grid Integration

The manner in which an SSP system provides power to the grid depends on the system developed. A large system (1.2 GW) using microwaves to transmit power to an earth receiver would be able to provide continuous power and at nearly a constant load to an Air Force base. Comparable systems using laser technology face the same issues as terrestrial-based photovoltaic system. The laser system cannot operate through clouds, although it can provide energy both day and night, weather permitting.

A.8.4 Concerns and Issues

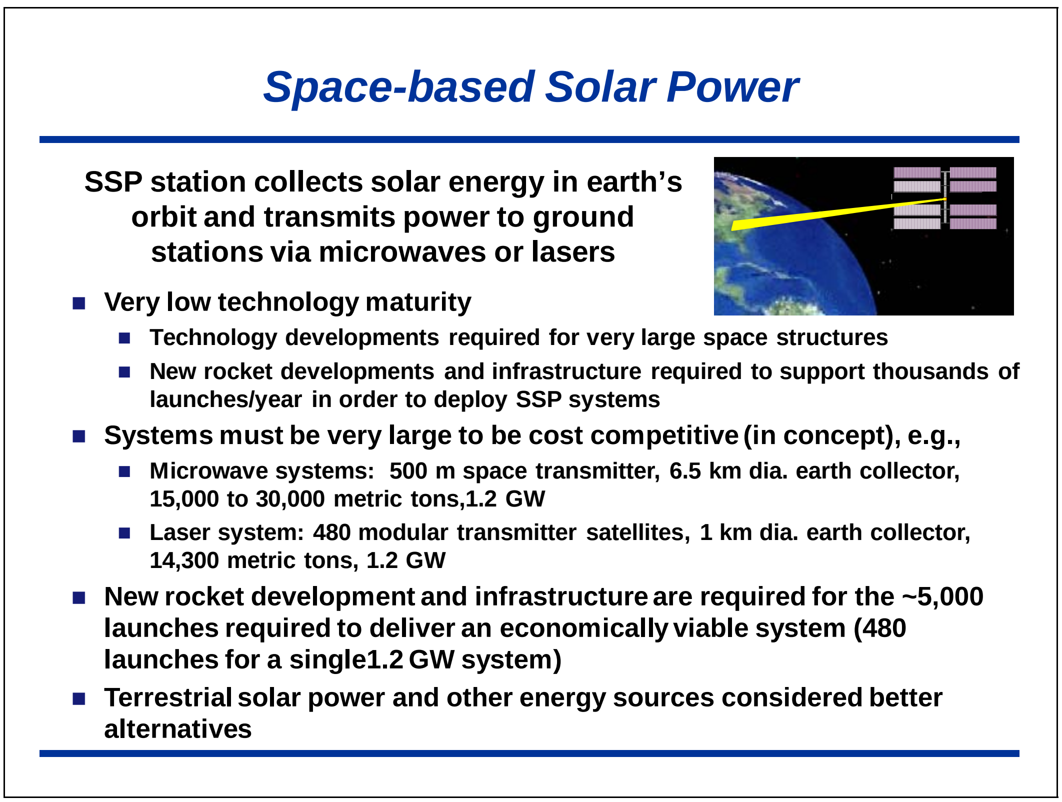

Figure A-13. Concerns for Space-Based Solar Power.

A.8.4.1 Maturity Level

SSP is at a very low maturity and technology level. In the near term, the current state of SSP technologies does not allow SSP to be economically competitive with alternative energy sources. Technology maturation is required for solar power, transmission technology,

large-scale space structures, and launch vehicle systems. In addition, environmental impacts of transmitting energy to earth need to be thoroughly evaluated. Even if the technology was sufficiently mature, a national initiative would be required to achieve such a large-scale and extremely costly development program. Investments in terrestrial based alternative energy sources are likely to be much more fruitful than SSP.

A.8.4.2 Cost

There is a low confidence with cost of power from SSP because of its low maturity level. One study estimated the cost be to $300-$400 per megawatt-hour (MWh). But before an SSP system can be delivered, a completely new launch vehicle infrastructure would have to be developed. The upfront costs would be tremendous.

A.8.5 Detailed Assessment

A.8.5.1 Background

In the late 1990’s and early 2000’s, there was a growing interest in SSP, and NASA (National Aeronautics and Space Administration) initiated a Fresh-Look study to reexamine the concept. Advancements in technology and increasing concerns with carbon dioxide emissions and global climate change[59] gave new hope to SSP proponents. Several concepts were examined for transmitting power from a space solar collection platform, including microwave, millimeter wave, and optical/laser wavelengths. The laser-based system has the benefit of operating with a much shorter wavelength than the others, allowing an aperture size of 25 centimeter (cm)[60] that is dramatically smaller than the 0.5 km aperture required for microwave transmissions. However, the laser system has the disadvantage that terrestrial solar arrays are required to collect the laser energy, whereas a microwave receiver consists of a relatively simple wire mesh. In addition, the laser system cannot transmit energy through clouds. The study further examined space platforms in low earth orbits, medium earth orbits, and geostationary earth orbits. Low and medium earth orbits offer the benefits of reduced aperture size and launch costs, but there are additional challenges with spacecraft control system and transmitting power to fixed locations on earth from those orbits.

The Panel considered the current state-of-the-art for SSP to determine whether it is now a viable means to delivering power to US bases, both in CONUS and OCONUS. From purely a conceptual perspective, SSP has great appeal since power can be collected continuously in geostationary earth orbits, can be delivered to remote military operations with terrestrial receivers, can be steered to different terrestrial receiving stations, and can be redirected to meet national emergencies or local energy shortages. However, there are still very significant technology, architectural, and infrastructure hurdles that suggest the SSP concept will not be an economical competitive candidate for alternative base energy unless truly remarkable (i.e., orders of magnitude) advances are made in launch capabilities.

59 Hoffert, et. al., 2002.
60 Penn & Law, 2001.

A.8.5.2 SSP Assessment

The sheer size of SSP systems presents development challenges and transporting them to orbit requires the development of a new launch vehicle system and associated launch infrastructure.[61] To be economically viable, several thousand of rocket launches a year are currently required. The current launch rate for the Space Shuttle, Delta IV, and Atlas V launch systems is of the order of 10s of launches per year, not 1,000s. Some might consider the issue to be merely one of economics, but the number of launches required to provide an economically competitive system raises serious issues with the consequences of anomalies and failures that should be expected statistically, based on past experience with the Space Shuttle and other launch vehicle systems. In addition the pollution and environmental impacts of such a significant increase in launch tempo have not been assessed.

The US government has not funded an in-depth assessment of SSP since NASA's Fresh-Look study in 1997 and NASA's Space Solar Power Exploratory Research and Technology (SERT) program in 2000.[62] While there have been other initiatives,[63] funding was not available to advance the studies beyond the concept design phase. Most of the concepts involve collecting solar energy and using microwaves to transmit the power to earth, yet lasers appear to be a very viable alternative. The size of the transmitter antenna and earth collector is governed primarily by wavelength of the transmitted energy. In support of NASA, The Aerospace Corporation conducted a study[64] of five operational SSP concepts that included:

- Sun Tower,
- Multi-strand Sun Tower,
- Perpendicular to Orbit Plane,
- Halo, and
- Laser.

The first four concepts used microwave frequencies for energy transmission to earth, and the last used laser wavelengths. For comparison purposes, the five concepts were sized to supply a 1.2 GW power output. The mass of the microwave systems ranged from approximately 15,200 to 29,500 metric tons. The transmitter antennas microwave systems are of the order of 0.5 km with a terrestrial footprint of 6.5 km diameter. The laser design consisted of a modular constellation of 480 satellites with a total mass of 14,300 metric tons, and a 1 km diameter solar collector at the ground site. It was also assumed that 10 of the 480 satellite systems would be launched, which reduces the cost per unit.

With the current state of technology, none of the SSP concepts are economically viable. It is not clear that the system could ever be economically viable, but if it were to reach a competitive state with current energy costs, at least four challenging technological break-through advancements would be required, along with a long-term government commitment. These challenges are summarized below and the cost benefits associated with overcoming the challenges are illustrated in Figure A-14 below.

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61 Penn & Law, 2008.
62 Penn & Law, 2001.
63 National Security Space Office, 2007.
64 Penn & Law, 2001.

Manufacturing cost must be decreased by a factor of three. This might be achieved by utilizing modular designs to gain the efficiencies of high manufacturing rates that reduce production costs, but this has not been demonstrated.

Increase the launch vehicle flight rate to about 4,800/year, or 1 launch every 2 hours, 24/7 (for 10 systems consisting of 480 satellites). This requires the development of a new reusable launch vehicle and the associated launch infrastructure. The current cost to launch is about $10,000 per kilogram (kg) and that needs to be reduced to about $400/kg. Past launch vehicle systems that have promised cost reductions have fallen short.

Increase end-to-end efficiency by 50%. This requires an investment in technologies that offer potential to improve the end-to-end efficiency of the system, including electronic, laser, and solar cell technologies.

Increase power density 4 times. To increase the power density, regulatory issues that prevent increasing the power density to a ground site must be addressed. Issues with human safety, aircraft safety, radio frequency interference, and control system reliability are all import factors, and could pose limitations on the system.

In addition to the technology advancements, the risk to investors must be reduced to enable SSP financing at a 90% debt ratio. The reduction in the cost of energy by implementing incremental technology improvements summarized above is a factor of about 2 to 3 (Figure A-14 below).

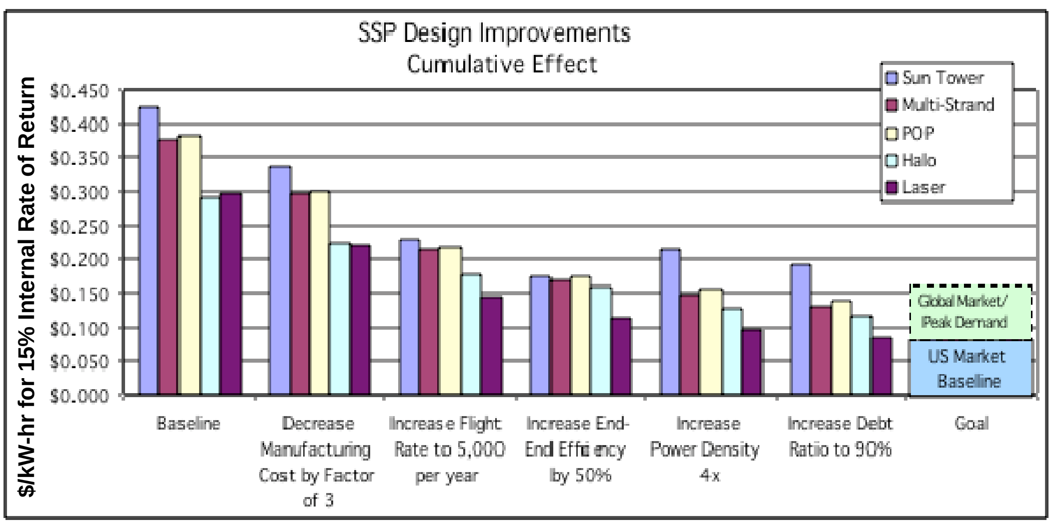

Figure A-14. Cost Estimates of SSP as a Function of Hypothetical Design Improvements.[65]

One benefit of the SSP laser system over a microwave system not taken into account by the Aerospace study[66] is the additional background solar energy that is collected by the collection of terrestrial solar arrays receiving the laser energy. The terrestrial solar arrays will be collecting energy from space 24/7 (when clouds are not present), but they will also be collecting ambient

65 Penn, SSP Systems Studies and Analysis, 2009.
66 Penn & Law, 2001.

solar energy during daylight hours. This additional energy was not included in the study, and would reduce the energy cost slightly.

Given the current state of the technology, SSP is not economically competitive. At this time, terrestrial PV technology incorporating conventional energy storage (batteries) provides a better economic choice for most of the populated planet. Assuming the same level of technology investment as would be needed for a SSP system, the cost of a conventional system would be driven even further down. A 20 MW terrestrial PV system requires installation of a 1 km by 1 km field populated with high efficiency tilted arrays.

A.8.5.3 Discussion

In the near term, the current state of SSP technologies does not allow SSP to be economically competitive with alternative energy sources. Technology maturation is required for solar power, transmission technology, large-scale space structures, and launch vehicle systems. In addition, environmental impacts of transmitting energy to earth need to be thoroughly evaluated. Even if the technology was sufficiently mature, a national initiative would be required to achieve such a large-scale and extremely costly development program. Investments in terrestrial based alternative energy sources are likely to be much more fruitful than SSP.

The debate on the utility of SSP has continued since the 1970s. A new study initiative might be warranted to quantify better the benefits and limitations of some sort of SSP. Any new study should be a collaborative effort among the Air Force, NASA, and DoE to establish a new baseline for the state-of-the-art. The last comprehensive study was performed by NASA in 1997 and 2000[67] and there was an essentially unfunded, open-source study by the National Security Space Office in 2007.[68]

A.8.5.4 Major Launch Requirements of Space Solar Power Systems

The technology for collecting and directing power in a space solar power system can be characterized in terms of the power per unit area S [watts per meter-squared (W/m^2)] and mass per unit area w [kilogram per meter-squared (kg/m^2)]. Their quotient provides the power per unit mass p [watts per kilogram (W/kg)]. The cost per watt-hour needed to be economically competitive decreases with total power P as indicated in Figure A-15 (below). This sets a minimum power level and a basic system mass P/p, which scales the total system mass, including propellant for orbit-raising, thereby determining the number of launches. At total power levels of a gigawatt and specific powers of less than 100 W/kg (corresponding to present spacecraft solar-photovoltaic arrays with subsequent stages of energy manipulation), the SSP system mass would exceed 10,000 tonnes. Detailed studies place the number of launches above a few thousand, even with very optimistic projections for SSP costs and launch capabilities. Scaling relations suggest that very major improvements in supporting spacecraft mass and launch vehicle design would be needed to counter the results of basic considerations to be competitive. This minimum power sets minimum values for system mass and the total number of launches required.

67 Mankins, 1997, and Penn & Law, 2001.
68 National Security Space Office, 2007.

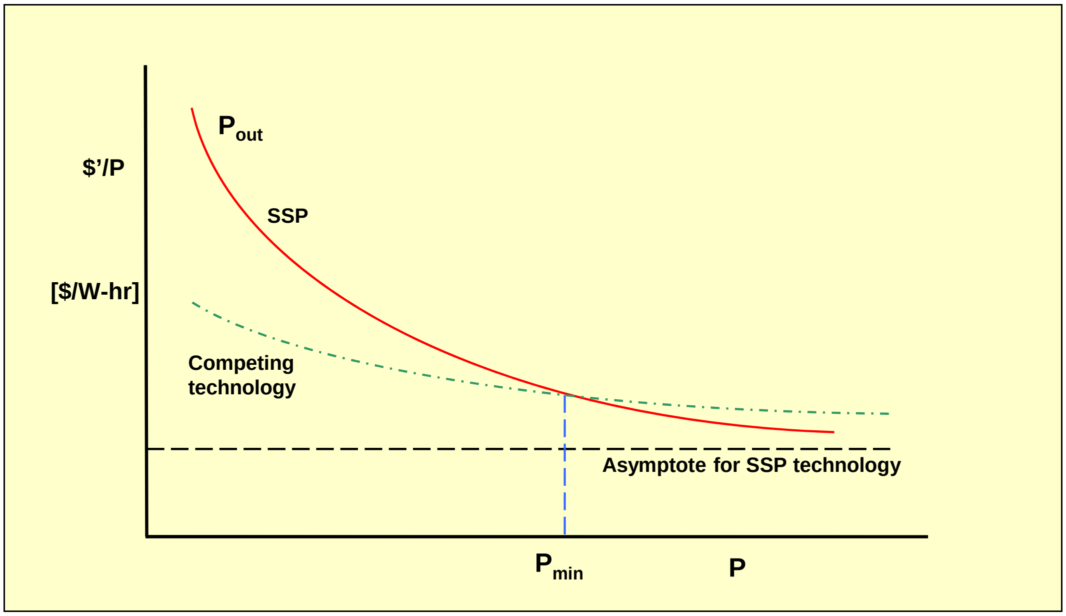

Figure A-15. Notional Plot of Cost/Watt-hour versus Watts Generated for SSP. (The crossing point indicates the minimum power output of the system at which SSP becomes competitive with (terrestrial) alternative energy projects.)

A.8.5.5 Derivation of Cost per Unit Power for SSP Systems

A basic problem that emerged from studies of SSP systems is the need for substantial launch resources in order to obtain economically attractive power levels. The following discussion attempts to outline this problem. It is not intended to substitute for more exhaustive analyses.

We may characterize the technology for collecting and directing power in a space solar power system in terms of the power per unit area S (W/m^2) and mass per unit area w (kg/m^2). Their quotient provides the power per unit mass p (W/kg). To obtain an output power to the user P, with a product Π_k of several efficiency factors η_k, requires a system mass M_s:

$$M_s = P/(p\ \Pi_k \eta_k) \qquad (1)$$

The total mass that must be launched is then M_{TL}:

$$M_{TL} = M_s\,(1 + f_F) + (M_s + M_{sc})\,[1 - \exp(-\Delta v/u)] + M_{sc} \qquad (2)$$

where f_F is a factor to account for structure needed to assemble the system in orbit (say, low earth orbit), M_{sc} is the mass of supporting systems for the spacecraft (e.g., communications) not proportional to the power of the system, and the term in brackets represents the relative amount of propellant to achieve the desired Δv with an exhaust speed u. Thus,

$$M_{TL} = [P/(p\ \Pi_k\eta_k)]\ \{(1 + f_F) + [1 - \exp(-\Delta v/u)]\} + M_{sc}\,[2 - \exp(-\Delta v/u)] \qquad (3)$$

The basic cost $\$_o$ of the full system may be written in terms of the total launch mass and the power that is handled by the ground station:

$$\$_o = k_L M_{TL} + k_g P \quad (4)$$

$$= P \{[k_L/(p\, \Pi_k \eta_k)]\ \{(1 + f_F) + [1 - \exp(-\Delta v/u)]\} + k_g\} + k_L\, M_{sc}\, [2 - \exp(-\Delta v/u)]$$

Very roughly, the cost rate $'of generating power P is the basic total cost divided by the time t_f for financing the system (which is similar perhaps to the depreciation/degradation time). Also, we need to account for the time lag before the system is economically competitive. Again roughly, we may write this as a factor $(1 + t_d/t_f)$, where the time t_d required to deploy the system includes the time t_L to launch all the mass into orbit. The cost per unit energy (e.g., mils/kW-hr) is then:

$$\$'/P = [(1 + t_d/t_f)/t_f\,]\ [\{[k_L/(p\, \Pi_k \eta_k)]\ \{(1 + f_F) + [1 - \exp(-\Delta v/u)]\} + k_g\} + (k_L\, M_{sc}/P)\ [2 - \exp(-\Delta v/u)]] \quad (5)$$

For $'/P equal to the value of the competing technology $(\$'/P)_{ct}$, we have a minimum power level P_{min} as indicated in Figure A-15 above:

$$P_{min} = k_L\, M_{sc}\, [(1 + t_d/t_f)/t_f\,]\ [2 - \exp(-\Delta v/u)] \,/\, \{ (\$'/P)_{ct} - [(1 + t_d/t_f)/t_f\,]\ \{[k_L/(p\, \Pi_k \eta_k)]\ \{(1 + f_F) + [1 - \exp(-\Delta v/u)]\} + k_g\}\} \quad (6)$$

This minimum power implies a minimum mass launched to orbit and therefore a minimum number of launches:

$$N_{min} = M_{TL})_{min}\, /m_L$$

$$= \{[k_L\, M_{sc}\, [(1 + t_d/t_f)/t_f\,]\ [2 - \exp(-\Delta v/u)] \,/\, \{ (\$'/P)_{ct} - [(1 + t_d/t_f)/t_f\,]\ \{[k_L/(p\, \Pi_k \eta_k)]\ \{(1 + f_F) + [1 - \exp(-\Delta v/u)]\} + k_g\}\}/(p\, \Pi_k \eta_k)]\ \{(1 + f_F) + [1 - \exp(-\Delta v/u)]\} + M_{sc}\, [2 - \exp(-\Delta v/u)]\}/m_L \quad (7)$$

where m_L is the cargo mass per launch vehicle. Division of Eqn 7 by $t_d > t_L$ would yield an underestimate of the launch rate. The expression for N_{min} displays the role of economic competition in determining the number of launches and the launch rate. It also indicates that the mass of support systems M_{sc} effectively substitutes for circulating power-fraction in specifying a minimum power level, size, and cost for SSP systems.

A.9 Nuclear Energy (Small Fission)

A.9.1 Summary

Several small nuclear plants have been built and operated in the past, but these were almost exclusively test reactors or prototypes for the much larger commercial plants now operating. Over the past few years, however, considerable interest has mounted to develop deliberately small reactors[69] with approximately 50 designs at some stage of development worldwide. The impetus for such development is to evolve commercially viable reactors sized for niche markets, military applications, small grids, and attempts to employ factory fabrication

69 Ingersoll, 2009.

and modularization to reduce construction costs for large energy installments. The International Atomic Energy Agency defines small rectors to be 300 megawatts-electric (MWe) or less. However, several designs are underway from 100 MWe down to approximately 5 MWe (a size range of potential interest to the Air Force). The range of designs includes cooling by conventional water, gas (helium or carbon dioxide), and liquid metal (sodium or lead systems).

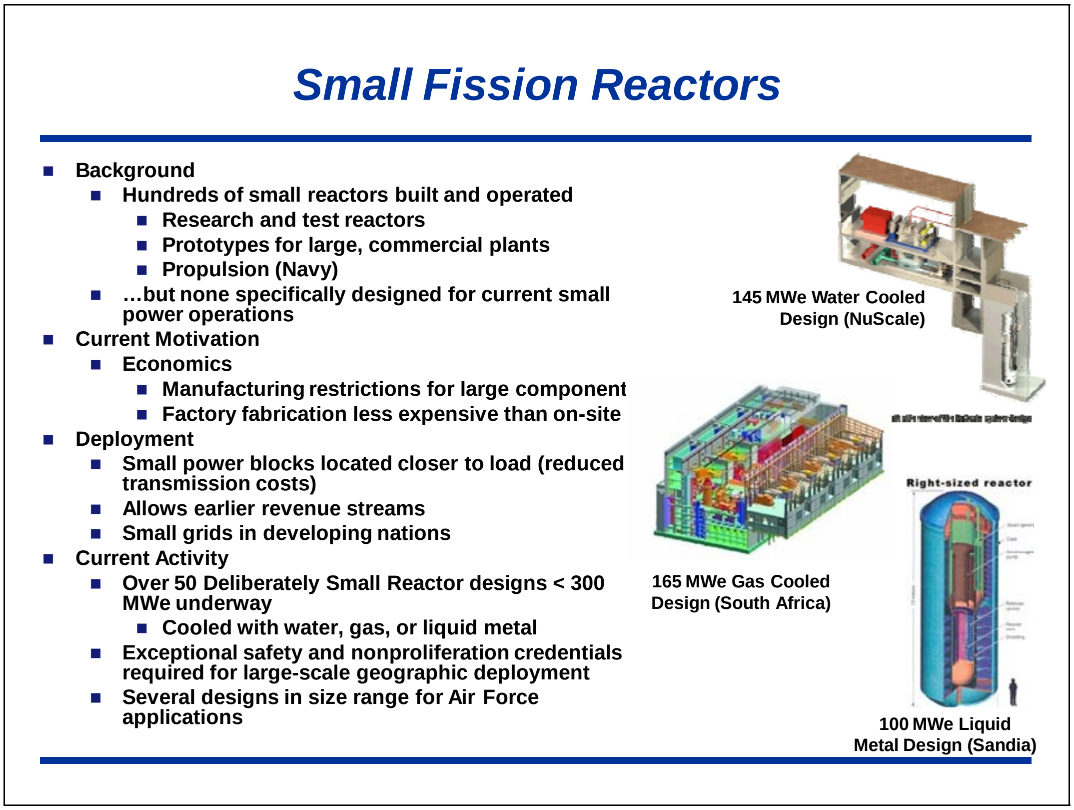

Figure A-16. Key Aspects of Small Nuclear Reactors.

A.9.2 Basic Principles

There are several technologies being pursued for small nuclear reactors (light water cooled, high-temperature gas-cooled reactors and liquid metal cooled fast reactors). Most of these reactors heat water to steam, use the steam to turn a turbine and generator, and generate direct current which is then inverted into alternating current. Some of the reactors are capable of driving more than one turbine/generator.

A.9.3 Capabilities and Payoffs

Table A-5 below summarizes the capabilities of small nuclear fission power modules.

Technology	Small Nuclear
Attributes	Uses current water coolant or more advanced coolant; small size (e.g. 50-150 MW)
Siting considerations	Underground siting enables higher security; social and political risk in siting
Storage Options	Estimated life of 20 years with no fuel change
Grid Integration considerations	Operates at high capacity factor as base load
Maturity Level	No small reactor designs currently licensed or operating; licensing and construction risk currently high
Cost ($/MWh)	?

Table A-5. Capabilities of Small Nuclear Reactors.[70]

A major advantage of deliberately small reactors is that they employ extensive passive safety features and the reactor component can be located underground. Both features are expected to allow such systems to be located much closer to populated areas (relative to the current 1,000 MWe and larger commercial reactors). Some of the designs allow the reactor to run for two or more decades without requiring shutdown for fuel reloading. This provides exceptional sustainability as well as impressive nonproliferation credentials. Current experience with present-day commercial power reactors has demonstrated very high capacity factors (over 90%) and there is no apparent reason that the smaller reactors cannot achieve similar or better performance.

A.9.4 Concerns and Issues

Perhaps the biggest impediment to the incorporation of small nuclear reactors for Air Force applications is the licensing that will be required. Once a particular design is selected for potential application, the time required to license and certify the reactor by the Nuclear Regulatory Commission (NRC) is a minimum of 4 years—and possibly longer. Hence, small reactors will not be available for near-term employment. Rather, mid-term operation should be the focus.

The cost of power from such systems is highly uncertain at this time, since no actual deliberately small commercial reactors have yet been built. The cost estimates from designers places the range somewhere in the $50 - $100 per megawatt-hour category. Whereas this is

70 *Ibid.*

likely in the range of other alternatives, a big advantage of nuclear is that (like geothermal) there is no need for an energy storage system.

A.10 Nuclear Energy (Large Fission)

A.10.1 Summary

Nuclear fission reactors exploit the huge amount of energy that is released during the nuclear fission process. The energy density in nuclear fission is orders of magnitude larger than that of chemical combustion processes. Whereas this incredible energy has been used to produce powerful nuclear weapons, it has also been effectively harnessed to produce safe, carbon-free, and cost-effective nuclear fission reactors, Figure A-17.

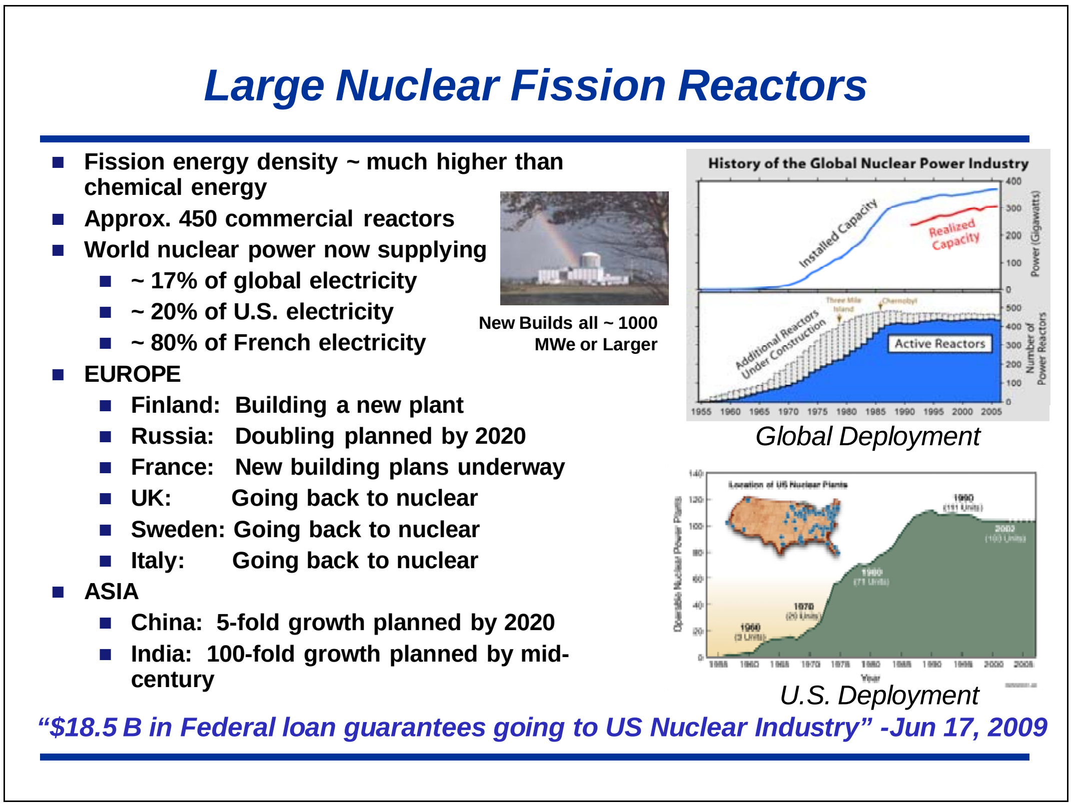

Figure A-17. Growth of Nuclear Power in the World in Recent Years.

A.10.2 Basic Principles

Most of the ~450 commercial nuclear power reactors currently in world-wide operation utilize ordinary water as the coolant (called light water reactors). About 2/3 of these are pressurized water reactors, where the water is pressurized to over 2,000 psi to prevent the water from boiling until it is heated to a high enough temperature to produce the high-quality steam required to rotate a turbine-generator system to make electricity. The other light water reactors are boiling water reactors where water boiling is specifically allowed to occur in the reactor at approximately 1,500 psi and then sent directly to the turbine. Other common coolants include gas (normally helium) and liquid metals (normally sodium) to accomplish other specific goals.

The first half century of nuclear power development has resulted in a fleet of over 100 large nuclear power plants in the United States that currently provide approximately 20% of the US electrical needs. On the global scale, approximately 450 nuclear reactors located in about 30 nations currently produce approximately 17% of the global electrical needs. As such, substantial maturing of the technology has been achieved. Given the proven attributes of nuclear power (e.g., reliable base load power production, low life-cycle costs relative to all sources other than hydroelectric, decades of safe operation, and carbon-free emissions during operation), most of the owners of the nuclear plants currently operating in the United States have petitioned the NRC for plant lifetime extensions of 20 years to extend their service from the originally licensed 40 years to that of 60 years. Many such plants have already received such approval. There is even considerable work underway to justify allowing the plants to run for several decades beyond 60 years. Similar work is underway in several nations.

Based on this favorable operating experience, enthusiasm for building new nuclear plants is mounting in many places in the world. The NRC has approximately two dozen applications in the early stage of processing for new builds within the United States. To help accelerate this new build, the Department of Energy announced on June 17, 2009 that four US builders would be allowed to split of some 18 billion dollars in guaranteed federal loan money to begin the second nuclear power area in the United States.[71]

On the world scene, Finland is well on the way of constructing a new European design sized at about 1,500 megawatts-electric (MWe). France has new construction underway, and even Sweden and Italy have voted to overturn the nuclear moratorium instituted after the Chernobyl accident and consider beginning a nuclear construction program. China has a massive nuclear power construction program well underway and plans a 5-fold growth by 2020, India is planning almost an order of magnitude increase in their nuclear power capacity in the next decade, and a 100-fold increase by the end of the century. Many developing nations are now posturing to build nuclear plants—including the petroleum-rich Gulf States who recognize that their oil reserves are finite.

So far, all of the new nuclear plant orders are for 1,000 MWe-class or larger designs, although this could change in favor of smaller units due to costs of constructing the larger components of these units, which require unique manufacturing capability. Nuclear reactors to be deployed in many of the developing nations will necessarily be relatively small due to the constraints of the electrical grid size of such nations.

A.10.3 Capabilities and Payoffs

Capabilities of large nuclear power generation systems for grid power are like those of the small nuclear plants, but on a greatly expanded scale. A typical USAF base requires 40MWe, only 4% of the output of a conventional nuclear power plant. If housed on a USAF base, such large systems would provide power for a large fraction of the surrounding region. The Panel considers that it would not be practical for a USAF base to host this scale of power generation.

71 Smith, R., 2009

A.10.4 Concerns and Issues

Size, vulnerability, and cost of operation of the large scale nuclear plant are outside the scope of this study.

A.11 Nuclear Energy (Fusion)

A.11.1 Summary

Nuclear Fusion

- **Nuclear fusion requires nuclei of light elements (e.g., deuterium, tritium) at high energy to overcome electrostatic repulsion and react.**
- **Concepts include confinement of nuclei by:**
  - **magnetic fields**
  - **Inertia**
  - **combined inertia and magnetic fields**
  - **other notions (e.g., electrostatic fields)**
- **Reactor conceptual-designs typically require gigawatt power levels for competitive rates**
- **Presently, experiments planned for magnetic and inertial confinement (tokamaks and laser-driven pellets) at B$-levels. Power reactors not expected before mid-century.**

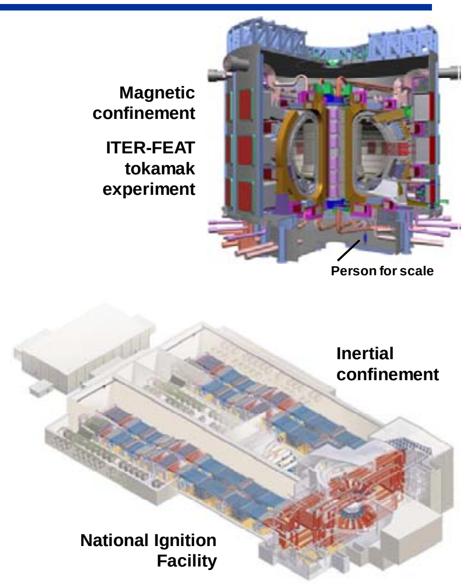

Figure A-18. Key Aspects of Nuclear Fusion Power.

A.11.2 Basic Principles

The following discussion summarizes controlled nuclear fusion power concepts to provide some completeness for the Panel's study report in regard to future possibilities. It should be stressed from the outset that power from controlled nuclear fusion is very much a long-term, basic research problem at this time. A power plant based on nuclear fusion reactions has been considered for approximately sixty years and has many conceptual manifestations. The key technical challenge is the containment of the exceedingly energetic nuclear fusion reactants that exist as high temperature plasma. Solutions to the problem can be separated into four main categories:

1) Magnetic-confinement,
2) Inertial-confinement,
3) Magnetic/inertial confinement (aka, magnetized-target fusion), and

4) Other approaches including particle beams, nuclear weapons, and the discovery of new physical phenomena.

The first two categories, in the forms of tokamaks (a Russian-invented machine that produces a toroidal magnetic field for confining a plasma) and laser-driven pellets, have received most of the attention and funding (at upwards of billions of dollars world-wide). The third area combines various elements of the first two in different schemes and has received intermittent attention at the level of several millions of dollars. The last category is multifarious, and in some cases, of dubious scientific merit. All concepts require that nuclei of light elements have relative kinetic energies sufficient to overcome their electrostatic repulsion, so they can approach close enough for nuclear reactions to occur at an adequate rate. For thermonuclear fusion, these energies are associated with the high energy tail of a velocity distribution-function at temperatures of 4-40 thousand electron-volts (keV). The principal problem of controlled thermonuclear fusion is then to sustain such temperatures for time periods sufficient to achieve economically-useful energy gain.

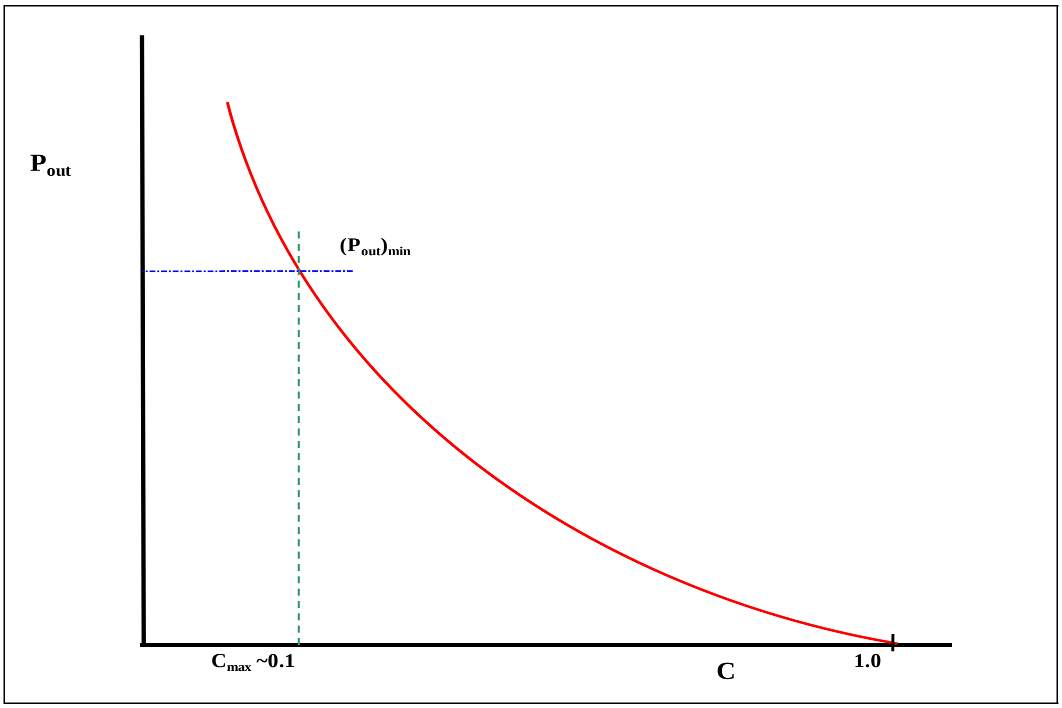

Figure A-19. Output Power versus Circulating Power Fraction for Fixed Pressure and Efficiency Factors.

Magnetic confinement concepts insulate the high temperature plasma by various arrangements of magnetic fields. The relative magnitudes of the magnetic energy-density and the plasma energy-density define two sub-categories of these arrangements. For the mainline program (i.e., tokamaks, such as ITER (International Thermonuclear Experimental Reactor)), the magnetic energy-density greatly exceeds that of the plasma, providing generally stable confinement and insulation, but at considerable extra energy and cost. Earlier attempts to confine plasma with magnetic fields of comparable energy-density surrounding the plasma encountered numerous dynamic instabilities that destroyed confinement about as quickly as the plasma could move, requiring pulsed operation. Inertial confinement concepts (e.g., the National

Ignition Facility) take this operation to a limit that does not require any magnetic field, using instead the temporary isolation of a hot region of plasma that occurs by application of energy in a very short pulse (less than 1 nanosecond for lasers; less than 100 nanoseconds for pulsed power). Such short pulse technology introduces significant costs that depend on power intensity (in addition to total energy). These costs may be substantially mitigated by introducing magnetic fields at the hot region, thereby creating, for example, the “hybrid” category of magnetized-target fusion that delivers energy over microseconds.

The creation of conditions for fusion power requires investment of energy derived from a portion of the electricity produced. If this portion is too great, however, then the cost of the remaining electrical power may not be economically competitive. The relative gain (Q) of fusion energy over the energy content of the particles providing the reactions determines the so-called circulating power fraction C that expresses the portion of the electricity used by the reactor itself. The relationship between Q and C involves several efficiency factors associated with converting electricity into particle energy and nuclear energy into electricity. Figure A-19 above displays a sketch of the output power of a fusion reactor as a function of the circulating power fraction. Typically, from detailed design studies of both magnetic and inertial confinement schemes, a maximum circulation of 10% results in minimum power levels above a gigawatt.

In Figure A-19 (above) the maximum value of C for economically competitive operation defines the minimum output power, which tends to scale the capital and operating costs.

A.11.3 Capabilities and Payoffs

Projected capabilities are described in Table A-6 below.

Technology	Nuclear Fusion
Attributes	Uses light nuclei (e.g., hydrogen isotopes) to generate energy from nuclear reactions. For world energy needs, this technology would access vast supplies of deuterium and lithium in seawater.
Siting considerations	Power reactor site would include facilities for processing materials.
Storage Options	No energy storage required.
Grid Integration considerations	Typical fusion power reactor would operate at steady GW levels, so integration is similar to other large power plants.
Maturity Level	Magnetic confinement approaching sub-prototype reactor levels in ITER experiments.
Cost ($/MWh)	No prototype data.

Table A-6. Capabilities of Potential Nuclear Fusion Reactors.

A.11.4 Concerns and Issues

Nuclear fusion power is not available today, and the technology development needed to bring it to reality is significant.

Projected total costs will scale with the output power, so minimum powers above several hundred megawatts may preclude acceptance of controlled fusion concepts. Indeed, a principal reason for the lack of acceptance of fusion power by the utility industry has been reluctance to introduce this technology at gigawatt power levels. With the power needs of an Air Force Base in the range of 50 MW, there is little need for us to consider controlled fusion for alternative base energy in the foreseeable future.

A.11.4.1 Calculation of Minimum Power of a Fusion Reactor

The energy obtained from fusion reactions depends on the square of the particle density, while the energy content of the particles is only linearly dependent on density. Thus, the relative nuclear energy compared to particle energy is:

$$Q = n^2F(w)t_d\, W_n / nG(w)\, W_p = nt_d(W_n/W_p)[F(w)/G(w)] \qquad (1)$$

where n is the particle density, t_d is the time for which conditions are maintained, W_n and W_p are the nuclear energy from the reaction and the particle energy, respectively, and F(w) and G(w) are functions of the distribution functions for the particle speeds (w). So-called "scientific break-even" corresponds to Q = 1. The product nt_d is usually quoted in terms of the Lawson criterion ($nt_d \approx 10^{14}$ s/cm^3) which refers to a fusion energy gain that equals the amount of energy needed to replace the energy of a (50:50) deuterium-tritium plasma (at 10 keV) after the nuclear energy had been passed through a thermodynamic system at 33% efficiency; i.e., Q = 3. Higher values of Q are needed to obtain net power from the fusion reactor. More complex analyses can refine estimates, but the following should suffice here to display the basic factors.

With a characteristic timescale t_r for energy replenishment and generation, the output power may be written as:

$$P_{out} = (QW_p/t_r)\eta_c(1 - C) \qquad (2)$$

where η_c is the efficiency of converting nuclear energy into electricity and C is the circulating power fraction. The power circulated back to the particles is:

$$P_p = (W_p/t_r)/\eta_p = CQ(W_p/t_r)\eta_c \qquad (3)$$

where η_p is the efficiency of converting electricity to particle energy. Thus, the necessary value of Q is:

$$Q = 1/C\eta_c\eta_p \qquad (4)$$

and the output power becomes:

$$P_{out} = (W_p/t_r\eta_p)(1 - C)/C \qquad (5)$$

From Equation 1, we can write the necessary particle density and duration to obtain the needed value of Q:

$$nt_d = Q\,(W_p/W_n)[G(w)/F(w)] = Q\,L(w) \tag{6}$$

The duration of fusion conditions depends on the approach. For magnetic confinement, this time may be dominated by diffusion, which scales as the square of a characteristic dimension x:

$$t_d = K_m x^2 \tag{7}$$

While for inertial confinement, the duration scales linearly with dimension:

$$t_d = K_I x \tag{8}$$

The particle density is then:

$$n = Q\,L(w)/K_{m/I}x^{2\div 1} \tag{9}$$

$$= p/(1 + Z)kT \tag{10}$$

where p is the particle pressure, Z is the ion charge-number and T is the temperature (for thermal systems); the subscripts "m" or "I" and exponent values 2 or 1 correspond to magnetic or inertial confinement, respectively. The combination of Equations 4, 9, and 10 provides the characteristic dimension for either magnetic or inertial confinement systems:

$$x = \{\, L(w)(1 + Z)kT \,/\, C\eta_c\eta_p K_{m/I}\, p \,\}^{1/(2\div 1)} \tag{11}$$

The particle energy then scales as:

$$W_p = g_{m/I}\,[\,p/(\gamma - 1)]\,x^3$$
$$= g_{m/I}\,[\,p/(\gamma - 1)]\,\{\, L(w)(1 + Z)kT \,/\, C\eta_c\eta_p K_{m/I}\, p \,\}^{3/(2\div 1)} \tag{12}$$

where $g_{m/I}$ is a geometric factor relating the volumes of fusion plasma to the cube of the characteristic dimension and γ is the specific heat ratio. The output power thus depends on the circulating power fraction:

$$P_{out} = [g_{m/I}\,[\,p/(\gamma - 1)]\,\{\, L(w)(1 + Z)kT \,/\, C\eta_c\eta_p K_{m/I}\, p \,\}^{3/(2\div 1)}/t_r\eta_p](1 - C)/C$$
$$= [g_{m/I}\,/(\gamma - 1)]\,\{\, L(w)(1 + Z)kT \,/\eta_c\eta_p K_{m/I} \,\}^{3/(2\div 1)}/t_r\eta_p p^{0.5\div 2}](1 - C)/C^{2.5\div 4} \tag{13}$$

This is sketched in Figure A-19 for fixed pressure and efficiency factors, indicating the determination of a minimum output power for a specified circulating power fraction. The actual shape of the curve will depend on the particular confinement scheme. Total costs will scale with the output power, so minimum powers above several hundred MW may preclude acceptance of controlled fusion concepts. Indeed, a principal reason for the lack of acceptance of fusion power by the utility industry has been reluctance to introduce this technology at the gigawatt power levels estimated by detailed studies of both magnetic and inertial confinement approaches to power reactors.

A.12 Ocean/Wave Energy

A.12 1 Summary

The Earth's oceans are a vastly underutilized energy resource. They cover 70% of the Earth's surface and contain a complex set of interacting forces that present a unique set of engineering and logistical challenges for energy harvesting.[72] Energy harvesting techniques harness the mechanical forces from waves, currents, and tides; the thermal energy from depth-dependent temperature gradients, and the osmotic pressure from salinity gradients (Figure A-20). In particular, the energy density of tide and wave sources can exceed that of solar and wind energy (Figure A-21).[73] Technologies to capture and convert the various ocean forces into energy are in various stages of development, from conceptual to fully commercialized.

A.12.2 Basic Principles

A summary of each of the five forms of ocean/wave power generation is presented in Figure A-20 below.

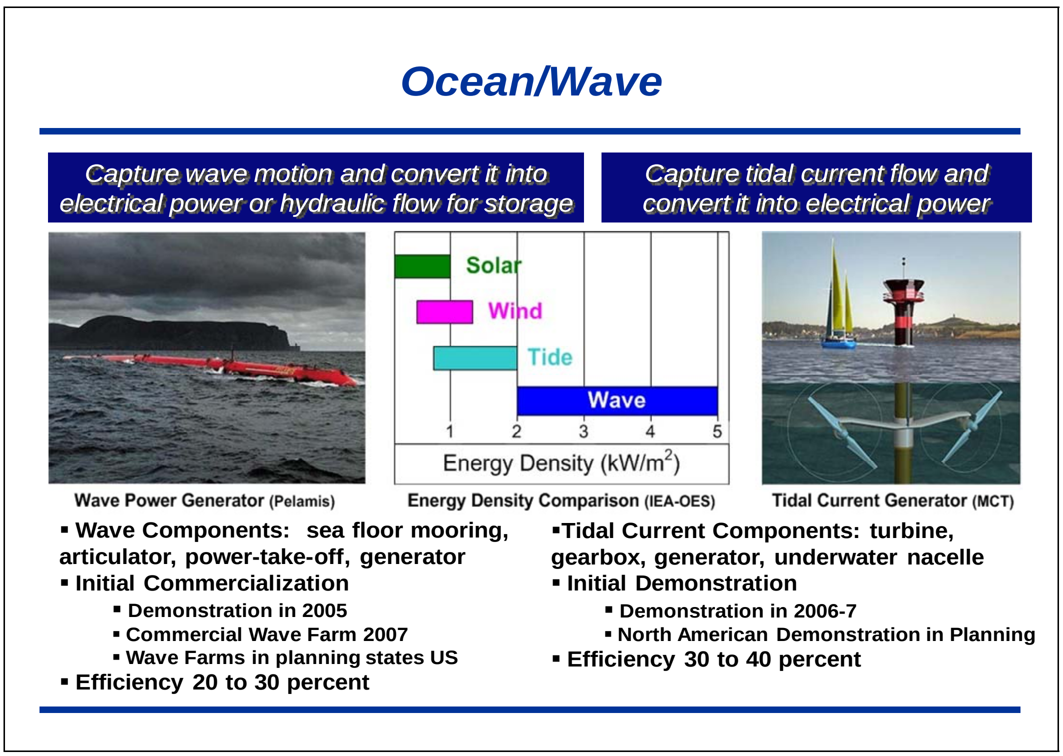

Figure A-20. Attributes of Oceanic Energy Generation.

72 Albeit & Niquen, 2004.
73 Brito-Melo & Bhuyan, 2009.

Alternative Energy Resources— Ocean Power

COMPARISON OF ATTRIBUTES OF OCEAN ENERGY HARVESTING TECHNOLOGIES

Technology	Attributes	Siting considerations	Storage Options	Grid Integration considerations	Maturity Level	Cost ($/MWh)*
Tidal/Ocean Current Barrage (Dam and Sluice Gate Method)	Shore bound high tide water is trapped by dam and released during low tide through conventional hydroelectric turbine; No carbon emissions	Requires construction of dam with sluice gate; May damage coastal ecosystem; 8% of Earth's land is coastline	Energy production is during low tide. Trapped water can be released at rates required to meet loading demands.	Controlled release rates are only valid for low tidal periods. Cyclical nature makes this technology a non-prime power source.	Largest barrage style power plant (France ~ 240 MW[1]) ; TRL 9.	Site Dependant
Tidal /Ocean Hydrokinetic	Converts predictable periodic and continuous flows of water into power; Turbine or kinetic capture structure is placed at or below surface level to capture tidal; No carbon emissions	Current flow rate should exceed 2 m/s to exploit current technology (Low current systems are in concept phase[5]);water depth is limiting factor	No intrinsic energy storage;	(Tidal) -- Variable but predicable with daily operation of approximately 22 hours[2]; (Constant Ocean Current) -- may be considered for prime power source	Large scale prototypes (Ireland 1.2 MW[4]); TRL 6-7	30-140 [2]
Wave Action	Converts periodic waves on a surface into electricity or a fluid with hydrostatic head; No Carbon Emissions	Needs to be located in large enough body of water to have ~1-2 foot waves and deep water placement (> 5m)	Intrinsic storage for some systems using fluid pumping; Most technology solutions do not have intrinsic storage capability	Variable production. Long transfer cables or pipes to shore to integrate with grid (3 miles plus depending on coastal water depth)	Large Prototype testing at full scale and some small commercial installations; (TRL 7-8[3])	20-120
Ocean Thermal	Temperature differential between depths. Rankin or Carnot cycle using working fluid and traditional turbines; Theoretical max efficiency is 7%	Requires significant depth differential (In excess of 400')	No intrinsic storage	Constant power source but requires large quantities of water due to low max efficiency.	Naval prototype at Hawaii; (TRL 6[3])	90-285 [3]
Salinity Gradient Technologies	Utilizes the osmotic pressure difference created between fresh water and salt water of approximately 26 bar equivalent to a 270 foot head of water	Needs to be located where a large brine water / fresh water presence exists	Storage of working fluids possible.	Constant Power Source limited to flow of fresh or salt water at location	TRL level 3 or 4, currently in demonstration phase in Norway[5]	80-141

Figure A-21. Ocean and Wave Technologies.

A.12.2.1 Wave Power

Waves are a product of off-shore and near-shore wind. The wind generates sheer stresses on the surface of the body of water which generates waves across the surface. Waves appear as linear, up down motions to most observers but consist of circular fluid motions. The energy at a given location is a function of the wave height, or amplitude, and the distance between the waves, or wavelength.

Wave Energy Converters can capture the energy of both locally produced and off-shore waves. Since both of these wave types are wind based, wave energy converters will have variable energy output and operating windows. Wave Energy Converters siting depends on the type of technology being utilized. In most instances, buoy and articulated wave generators need to be moored in areas were the water depth is greater than the maximum wave height. For example the Ocean Power Technologies Power Buoys was installed at the Marines Corps Base Hawaii in 30 meters deep water. However, some systems need to be near-shore or onshore.[74]

Currently, the amount of average wave energy for Department of Defense (DoD) CONUS sites and other permanent military installations has not been compiled or mapped.[75] Primarily this is due to the lack of funding by the Department of Energy for the National Renewable Energy Laboratory to evaluate wave power potential off the coast of the United States; although this has changed with the Marine Renewable Energy Research and Development Act of 2007.

74 Brito-Melo & Bhuyan, 2009.
75 Pontes & Candelária, 2009.

Most wave energy converters directly connect the wave motion to electrical power generation. Some systems, to reduce off shore system complexity, utilize pumping of water to on shore facilities for power generation using turbines.[76] Since the pumped water can be stored above the turbine in an impoundment or tank, some of the energy can be stored to provide load-following capability similar to a terrestrial hydroelectric dam.

The stated energy costs for Wave Energy Converters are based on the stated price quotes of various design manufacturers. Pelamis Wave Power Limited estimated a total capital and operational cost of their systems to be $200, to $300 per kW, or a cost of 20 to 120 dollars per megawatt-hour (MWh).[77]

A.12.2.2 Tidal Power

Tides are a result of lunar and solar gravity acting on the seas of the rotating earth. Tidal energy conversion utilizes the variation in overall water height created by spring and neap tides. Since tidal power is generated by gravity, it is an inexhaustible supply of energy independent of any other form of renewable energy. It is a discontinuous but predictable energy source, with a daily variation between rising and ebb tide and a longer term variation over a 27 day period.[78]

Tidal barrages are specialized impoundments along the shore which allow rising tide water to be impounded until ebb tide conditions occur when the water is released back to the ocean.[79] Tidal pool systems operate on the same principle but do so off shore in a manmade impoundment rather than a terrestrial feature. Modern tidal generators can generate power both on ebb and flood tides.

Barrage and tidal pool systems require a sufficiently large variation in flood and ebb tide levels to generate electricity economically. Current technology calls for a difference in tide heights of approximately 2 to 3 meters.[80] Barrage systems need to be located on estuaries as the most economical location.

Tidal Barrage systems tend to have highly variable costs depending upon the hydrology and topography of the site. An estuary with a narrow opening will require far lower capital outlay than a wide mouthed estuary. Typically there are high capital investment costs for barrage installations. The tidal barrage system proposed for the Severn Bay in Wales has had reported capital costs from $0.70/kWh to $1.20/kWh.[81]

A.12.2.3 Hydrokinetic

Currents in the ocean fall into two categories, marine currents, and tidal currents. Marine currents, such as the Gulf Stream, are generally continuous streams of water generated by a variety of sources such as salinity, wind, temperature, and the earth's rotation. The energy density of a marine current at any given point is affected by the topology of the bottom, shore, and the interaction of other currents.[82]

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76 Cable et. al., 2008.
77 *Ibid.*
78 Bedard: Overview, 2006, and Bedard: North America Tidal, 2006.
79 Khan & Bhuyan, 2009.
80 Baker & Leach, 2006.
81 *Ibid.*
82 Brito-Melo & Bhuyan, 2009.

In many instances, water current energy converters are similar in appearance to wind turbines. However, for an identical sized sweep area, the water current generator will have access to 100 times the energy than that of a wind generator. Vertical axis turbines, horizontal axis turbines, and ducted turbines have all been suggested for capturing tidal energy. These systems suffer from some of the same problems that wind turbines encounter, such as low gear box efficiency and high starting torque. They must also endure long term immersion in salt and brackish water. Some designs attempt to deal with this issue by placing the generator above the water level, although this can result in surface navigation hazards. A handful of firms have proposed using tidal generators based on venturi pumps or hydrofoils.

Today, the locations in which current energy converters can be economically deployed are quite limited. There is a great deal of potential for the utilization of marine current at DoD facilities located along the CONUS coastlines. However, actual implementation may not be practical, there have not been any demonstration projects using marine currents such as the Gulf Stream or the Pacific Current to inform investment decisions.

The anticipated costs for ocean current technology have a wide range and a large uncertainty. Data on tidal current technology deployment costs at full scale are limited to Seagen and the Kobold system. The Electric Power Research Institute (EPRI) generated a series of cost projections as part of an international (United States and Canada) feasibly study for a North American tidal power demonstration. This cost analysis was used as the basis for cost of energy projections for tidal power. In general these estimates are considered to be plus or minus 30% of the actual costs per unit.[83]

A.12.2.4 Ocean Thermal

Ocean Thermal technology utilizes the temperature gradient between warm surface water and cold deep ocean water. Ocean surface temperatures near the equator approach 77º Fahrenheit (25º Centigrade) in a 50 meter (165 foot) thick surface layer.[84] This layer acts as a global solar thermal collector, collecting 90% of the sun's radiation on the planet. Under the surface layer, the water temperature drops to 43ºF (6ºC) at a depth of approximately 640 meters (2,100 feet) and continues to decrease to 39ºF (4ºC) at a depth of approximately 1 kilometer (3,281 feet).[85]

Most proposed ocean thermal energy systems utilize a conventional organic Rankine power generation cycle.[86] The Rankine cycle uses a working fluid that is vaporized in an evaporator and then fed to a turbine to produce power. The gas is then condensed back into a liquid and pumped back to the evaporator. In ocean thermal energy cycles, the heat of the surface water is used to evaporate the working fluid while the cold deep sea water is used to cool the gas dispelled from the turbine.[87] Proposed ocean thermal energy systems are classified by the working fluid of the cycle, open cycles utilize seawater while closed systems utilize a volatile refrigerant.

Existing and proposed ocean thermal energy systems need to expend a great deal of energy pumping the sea water into the active portion of the generator. It is been estimated that

83 Khan, Bhuyan, & Moshref, 2009, and National Oceanographic and Atmospheric Administration, 2007.
84 Cable et. al., 2008.
85 *Ibid.*
86 *Ibid.*
87 Brito-Melo & Bhuyan, 2009.

26% of the power actually generated by the plant needs to be utilized by the plant itself, mostly for pumping seawater.[88]

There is no intrinsic energy storage available in ocean thermal energy systems. Since the power source is the natural temperature gradient between the surface and the deep, it can operate as a base load source (constant power output) without need for any energy storage to supplement "down" periods.

The energy costs currently reported for ocean thermal energy were found to be anywhere from \$0.09/kWh to \$0.285/kWh. These values were calculated based on the reported installed costs that varied from \$5,800 to \$18,000 per kW that were provided by industry to the US Navy for its Ocean Energy Survey report.[89]

A.12.2.5 Osmotic Pressure

The osmotic pressure difference between salt water and fresh water can be used to generate energy. The generator consists of a sealed cell with two compartments that are separated by a semi-permeable membrane. When salt water and fresh water are placed into the separate compartments, fresh water diffuses through the membrane into the salt water solution in order to equilibrate the salt concentration in the two fluids. This produces a pressure differential that can be used to power a traditional turbine. The amount of pressure generated is known as the osmotic pressure. Osmotic power generation technologies use fresh water with ocean salt water to generate pressure.

Osmotic pressure generation needs a supply of fresh water and salt water. The potential power generation is a function of the limiting supply of either of these components. Pilot experiments have been located on such places as the Dead Sea and the North Sea. The most significant limitation on deployment of this technology is the environmental impact caused by the creation of large amounts of brackish water. For sites using salt water wells, the brackish water has serious environmental consequences for a fresh water ecosystem and must be impounded, evaporated and the salt recovered. For regions of the world where natural mixing of salt and fresh water occurs (e.g., outlet of a fresh water river into the ocean), reducing the fresh water plume into the salt water can adversely affect the estuary environment and dependent aquaculture.[90] Existing man-made water plumes may be the most advantageous to utilize since the fresh water plume has already had an effect and the increase in plume salt concentration would provide a partial restoration of the ecosystem.

The estimate for energy cost of operating a salinity osmosis generation plant was found to be \$0.076 to \$0.140 per kWh. This estimate is based on the cost of a reverse osmosis plant with pressure recovery, with a capital price of \$3 M per 12.5 million gallons per day capacity and a \$1 M capital cost for the turbine generation system per Megawatt of installed capacity.[91]

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88 *Ibid.*
89 Cable et. al., 2008.
90 Jones & Finley, 2003.
91 TSG Water Resources, 2003.

A.12.3 Capabilities and Payoffs

Table A-7 below compares the relevant attributes of wave and tidal power generation systems.

Technology	Attributes	Siting Considerations	Storage Options	Grid Integration Considerations	Maturity Level	Cost ($/MWh)
Ocean Power: Wave	Converts periodic waves on a surface into electricity or a fluid with hydrostatic head; No Carbon Emissions	Needs to be located in large enough body of water to have ~1-2 foot waves and deep water placement (> 5 m)	Intrinsic storage for some systems using fluid pumping; Most technology solutions do not have intrinsic storage capability	Variable production. Long transfer cables or pipes to shore to integrate with grid (3 miles plus depending on coastal water depth)	Large Prototype testing at full scale and some small commercial installations; (TRL 7-8)	20-120
Ocean Power: Tidal	Shore bound high tide water is trapped by dam and released during low tide through conventional hydroelectric turbine; No carbon emissions	Requires construction of dam with sluice gate; May damage coastal ecosystem; 8% of Earth's land is coastline	Energy production is during low tide. Trapped water can be released at rates required to meet loading demands.	Controlled release rates are only valid for low tidal periods. Cyclical nature makes this technology a non-prime power source	Largest barrage style power plant (France ~ 240 MW**1**); TRL 9.	Site Dependant

Table A-7. Comparison of Capabilities and Attributes of Oceanic Energy Generation.

A.12.3 Concerns and Issues

One of the major obstacles with any wave resource projects is lack of long-term ocean wave measurements inside the 100-meter-depth contour, where refraction effects result in spatially inhomogeneous wave parameters. Lack of data makes it difficult or impossible to mark the optimum locations for wave energy converters (WECs). Visual inspections could lead to places with good but short-term yield or to places with sporadic surges exceeding the safety threshold. An ideal WEC site would supply consistent power throughout the year, which of course is precluded by seasonal weather variation and wind patterns.

These unavoidable variations in wave parameters also impose changes in WEC outputs. When the WEC runs at wave conditions below what it is designed for, it is called part-load operation. Similarly, wave conditions exceeding design conditions impose overload operation. At these two operating conditions, WEC output is reduced (i.e., the energy conversion efficiency drops). The overload could also lead to significant structural damage.

Load variation is unavoidable in WECs, and the variations can be inherent to the cycle of the wave itself or could be imposed as a result of external conditions, such as weather profile, bathymetry, and surface friction.

One of the most critical obstacles to developing WEC technology is the lack of research support to motivate coordinated efforts in advancing the technology. In contrast, the European Commission has increased its support for WEC projects since the beginning of the Joule Program.[92] The last decade of research and development represented more than 20 large projects backed by hundreds of millions of dollars.

To date, there is a limited amount of data available on the environmental impact of wave farms that are in continuous operation. Relative to other forms of electricity generation, including other renewable sources such as sunlight or wind, wave energy conversion is expected to cause little adverse environmental impact. Once the wave farm is installed, the main impacts will come from increased operational activity to maintain the devices. Several federal, state, and local authorities would have overlapping regulatory jurisdiction over a WEC project. An exhaustive list of the maritime boundaries recognized by local, state, federal, and international law is beyond the scope of this report.

A.13 Biofuel Energy

A.13.1 Summary

Bio-fuels are produced from living organisms or from metabolic by-products (organic or food waste products). In order to be considered a biofuel the fuel must contain over 80 percent renewable materials. It is originally derived from the photosynthesis process and can therefore often be referred to as a solar energy source. A general outline of the biofuel life cycle is provided in Figure A-22. There are many pros and cons to using bio-fuels as an energy source.

Bio-fuel is defined as solid, liquid or gaseous fuel obtained from relatively recently living biological material and is different from fossil fuels, which are derived from long dead biological material. Various plants, plant-derived materials, and animal byproducts are used for biofuel manufacturing.

Globally, bio-fuels are most commonly used to power vehicles, heat homes, and for cooking. Bio-fuel industries are expanding in Europe, Asia, and the Americas. Recent technology developed at Los Alamos National Laboratory even allows for the conversion of pollution into renewable bio fuel. Agro-fuels are bio-fuels which are produced from specific crops, rather than from waste processes such as landfill off-gassing or recycled vegetable oil.[93]

A.13.2 Basic Principles

There are two common strategies of producing liquid and gaseous agro-fuels. One is to grow crops high in sugar (sugar cane, sugar beet, and sweet sorghum) or starch (corn/maize), and then use yeast fermentation to produce ethyl alcohol (ethanol). The second is to grow plants that contain high amounts of vegetable oil, such as oil palm, soybean, algae, jatropha, or pongamia pinnata. When these oils are heated, their viscosity is reduced, and they can be burned directly in a diesel engine, or they can be chemically processed to produce fuels such as biodiesel. Wood

92 Beyene & Wilson, 2008.
93 The Globalist, 2006.

and its byproducts can also be converted into bio-fuels such as wood-gas, methanol, or ethanol fuel. It is also possible to make cellulosic ethanol from non-edible plant parts, but this can be difficult to accomplish economically.[94]

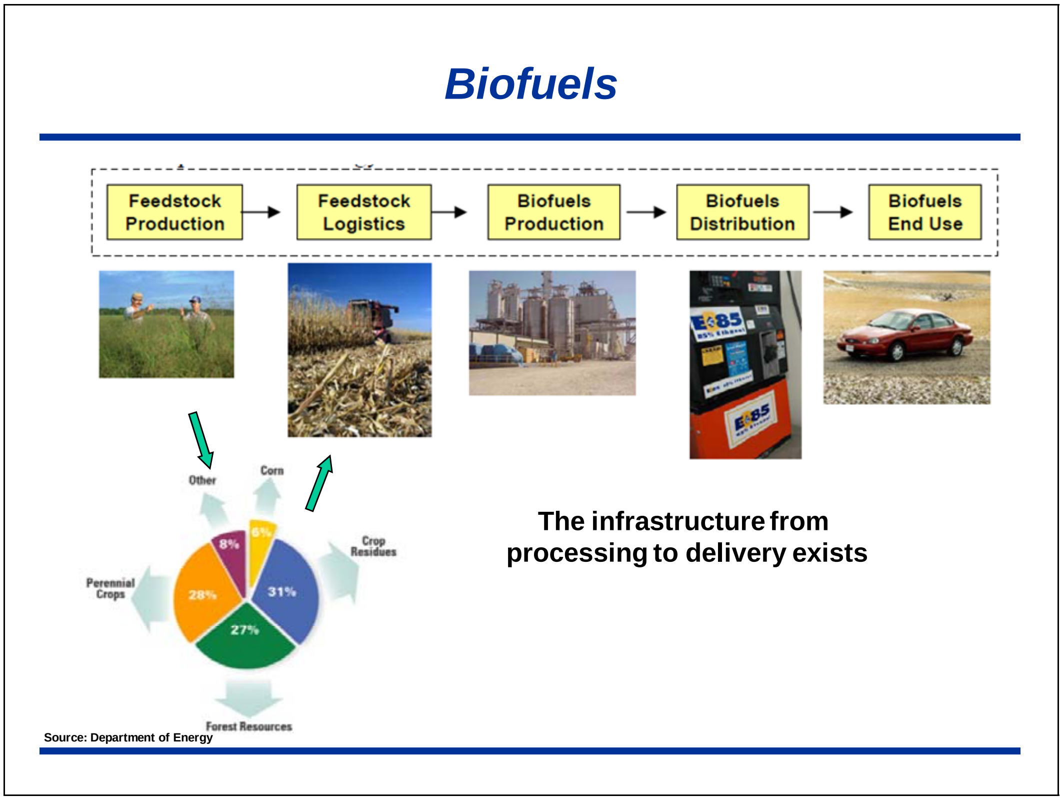

Figure A-22. Basic Principles of Bio-fuel Generation.

A.13.3 Capabilities and Payoffs

Energy crops have the potential to reduce greenhouse gas emissions by more than 100% (relative to petroleum fuels) because such crops can also sequester carbon in the soil as they grow.[95] In the future, the type of processing energy used will be more relevant. A biofuel plant that uses biomass energy could contribute far more to reducing greenhouse gas emissions than one using coal energy.

Biodiesel contains no sulfur or aromatics, and use of biodiesel in a conventional diesel engine results in substantial reduction of unburned hydrocarbons, carbon monoxide and particulate matter. A US Department of Energy study showed that the production and use of biodiesel, compared to petroleum diesel, resulted in a 78.5% reduction in carbon dioxide emissions. Moreover, biodiesel has a positive energy balance. For every unit of energy needed to produce a gallon of biodiesel, 3.24 units of energy are gained.[96]

94 Demirbas, 2009; Gnansounou, et. al., 2009; and Obbard, 2009.
95 The Global Benefits of Biofuels, 2006.
96 The National BioDiesel Board, 2009.

Because biodiesel can be manufactured using existing industrial production capacity, and used with conventional equipment, it has been promoted as providing an opportunity to address our national energy security issues.[97]

In February 2008, Boeing, Virgin Atlantic, and General Electric (GE) Aviation proved the technical feasibility of using biofuels in a commercial jetliner during the first biofuel flight using a sustainable biofuel mixed with kerosene-based fuel. That effort was followed by a sustainable biofuels test flight in December with Air New Zealand and Rolls-Royce. In early 2009, Boeing conducted another series of evolutionary test flights with Continental Airlines and GE Aviation, and Japan Airlines and Pratt & Whitney, respectively, with all of the flights emphasizing sustainable biofuels that potentially can be applied to the existing airplane fleet to reduce CO_2 emissions, regardless of the feedstock origin.[98]

A.13.4 Concerns and Issues

Corn-based ethanol is currently the most widely used biofuel in the United States, but it is also the most environmentally damaging among crop-based energy sources. A new article published in Conservation Biology, a publication of the Society for Conservation Biology, qualitatively contrasts major potential sources of biofuels, including corn, grasses, fast-growing trees, and oil crops.[99] The study highlights their relative impacts on the environment in terms of water and fertilizer use and other criteria to calculate the environmental footprint of each crop.

"The central goals of any biofuel policy must minimize risks to biodiversity and to our climate," says lead author Martha Groom of the University of Washington. She recommends the further use of algae and fast-growing trees as biofuel sources because they yield more fuel per acre than any feedstocks currently being pursued.

As well as comparing potential biofuel feedstocks, the study also recommends a number of major principles for governing the development of environmentally friendly biofuels. Feedstocks should be grown according to sustainable and environmentally safe agricultural practices with minimal ecological footprints (the area of land required to grow and support sufficient amounts of the crop). In particular, emphasis should be placed on biofuels that can sequester carbon or have a negative or zero carbon balance. The Panel recommends that these issues also be considered for any biofuels projects located on USAF bases.

Controversy over the benefits of using corn-based ethanol in vehicles has been fueled by studies showing that converting corn into ethanol may use more fossil energy than the energy contained in the ethanol produced. A recent Massachusetts Institute of Technology analysis shows that the energy balance is actually so close that several factors can easily change whether ethanol ends up a net energy winner or loser.[100]

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97 *Ibid.*
98 The Boeing Company, 2009.
99 Groom et. al., 2008.
100 Groode & Heywood, 2008, and Stauffer, 2007.

A.14 Novel Processed Fuels

A.14.1 Summary

Novel processed fuels can be thought of as synthetic variants of traditional liquid fuels. They may be derived from fossil sources (like coal), or from non-fossil sources (like biomass). Because hydrogen can be combined with carbon dioxide from the atmosphere to produce a hydrocarbon fuel, hydrogen can also be considered a source of novel processed fuel. Novel processed fuels provide a unique opportunity to couple directly into the entire infrastructure, cross-couple many unconventional energy sources throughout the infrastructure, provide a more diverse energy mix (particularly in transportation fuels), and provide a transition path to a hydrogen economy. One of the most effective ways to store, transport, and utilize hydrogen within the existing infrastructure is to attach a carbon molecule to the hydrogen to produce a novel processed fuel (Figure A-23 below).

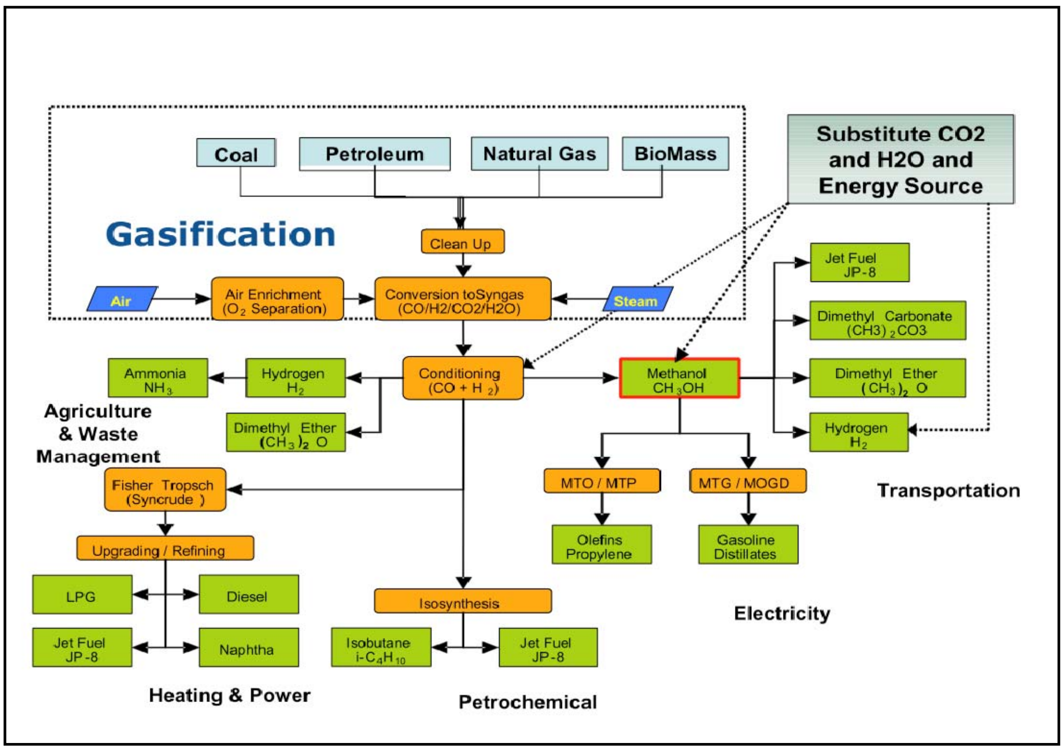

Figure A-23. Various Methods to Produce Novel Fuel Systems.

A.14.2 Basic Principles

The synfuels diagram of Figure A-23 provides several possible paths between hydrocarbon energy sources and synfuels that can be used as a baseline to develop and transition to novel processed fuels derived from water, carbon dioxide, and energy sources such as heat, light, electricity, and nuclear. The carbon dioxide would initially come from sequestered stack gases such as coal burning plants, although in the long-term it could be directly extracted from the air, just as green plants do. The primary energy source would come from nuclear or solar, in particular hydrogen produced from these sources, with the possibility of optimizing the paths

between water, carbon dioxide, and heat and the novel processed fuel without explicitly creating hydrogen or carbon monoxide.

A.14.2.1 Nuclear Hydrogen Initiative

The goal of the Nuclear Hydrogen Initiative (NHI) is to demonstrate the economic, commercial-scale production of hydrogen using nuclear energy. If successful, this research could lead to a large-scale, emission-free, domestic hydrogen production capability necessary to support the production of chemical feedstocks, liquid petroleum products, and a future transition to a hydrogen production economy.

A.14.2.2 Why Use Nuclear Energy to Produce Hydrogen?

Hydrogen forms the backbone of our industrial and transportation sectors. From an industrial perspective, hydrogen is used in the refining of petroleum into transportation fuels, especially heavy crude oils that are deficient in their hydrogen content. Almost as important is the use of hydrogen in the creation of chemical feedstocks needed in the manufacturing of plastics and thousands of consumer products. In addition to conventional hydrocarbon transportation fuels, hydrogen offers significant promise as a direct energy carrier for the transportation sector. It is generally thought that the direct use of hydrogen in transportation would reduce US dependence on foreign sources of petroleum, while enhancing our national security. Significant progress in hydrogen combustion engines and fuel cells is bringing hydrogen-powered transportation closer to reality. For example, the USAF maintains a hydrogen fueling station and hydrogen fueled vehicles (as a technology demonstrator) on Hickam AFB in Hawaii.

The primary challenge to the increased use of hydrogen as part of the Nation's overall energy infrastructure is the cost associated with its production, storage, and delivery. Hydrogen is the most common element in the universe and can be produced from readily available sources such as methane and water. However, existing hydrogen production methods are either inefficient or they produce greenhouse gases. Nuclear energy has the potential to efficiently produce large quantities of hydrogen without producing greenhouse gases and hence, to play a significant role in hydrogen production.

A.14.2.3 Developing an Integrated Hydrogen Program

NHI is a component of the research and development effort to reverse America's growing dependence on foreign oil and expand the availability of clean, abundant energy. Hydrogen is produced today on an industrial scale in the petrochemical industry by a process of steam reforming, using natural gas as both source material and heat source. Carbon dioxide is generated as a by-product.

A carbon-free option for the future could be the use of advanced nuclear technology to produce hydrogen. High temperature heat from an advanced nuclear system could be supplied to a hydrogen-producing thermochemical, or high temperature electrolysis plant through an intermediate heat exchanger. Such an arrangement could provide high efficiency and avoid the use of carbon fuels and the resulting carbon dioxide. NHI is exploring a range of hydrogen production technologies that could enable various Generation IV systems to produce hydrogen across a range of temperatures; however, high temperature processes show the greatest promise. High temperature process heat would be available from the Generation IV reactor concept of the

Very High Temperature Reactor, which is being developed in the United States as the Next Generation Nuclear Plant.

Significant R&D will be required in order to complete a commercial-scale demonstration. The hydrogen production system and heat transfer components, such as intermediate heat exchangers, will require the evaluation and development of high-temperature, corrosion-resistant materials.

NHI is being implemented in close cooperation with programs in other DoE offices that are conducting hydrogen R&D—the Office of Energy Efficiency and Renewable Energy, Fossil Energy, and Basic Energy Sciences. This cooperation eliminates redundancy while ensuring that R&D is complementary. Nuclear Engineering has also established substantial cooperation in this area with its international research partners.

A.14.3 Capabilities and Payoffs

Table A-8 below summarizes the capabilities of both sunshine to petrol (S2P) and nuclear fuels generation.

Technology	Attributes	Siting considera-tions	Storage Options	Grid Integration considerations	Maturity Level	Cost ($/gal)
S2P	Renewable, green fuel; reuse CO2; based on existing collectors; locate in desert	Resource location is limited; requires land	Produces fuel; no other needed, but could be coupled with thermal storage for CSP	Fuel couples directly into the grid	Electricity / Electrolysis is ready today; thermo-chemical is in the R&D phase	3-15
Nuclear Fuels	Green fuel; High energy density portable source	Security reqts; water reqts.	None needed; produces fuels	Fuel couples directly into the grid	Electricity/ Electrolysis is ready today; thermo-chemical is in the R&D phase	3-15

Table A-8. Capabilities and Payoffs for Novel Processed Fuels.

A.14.4 Concerns and Issues

The production of liquid fuels (i.e., jet fuel) is possible via any electricity source, be it renewable-, nuclear-, or fossil-derived, although fossil doesn't make sense from a carbon-constrained perspective. The largest impediment to liquid fuel production by this path is cost. Presently, it is more efficient use heat derived from solar or nuclear sources to convert water and carbon dioxide into syngas (thermo-chemical processing) rather than to use electricity derived from solar or nuclear energy sources (electrolytic processing). Unfortunately, no high temperature nuclear gas reactors are available in the United States today and the thermo-chemical processing techniques are still in the R&D phase. On the other hand, these

technologies provide a major payoff by utilizing the existing infrastructure, developing a “green liquid fuel,” and, in the case of nuclear, supplying a secure source of fuels once the reactor is in place.

A.15 Biomass

Biomass

- **Dead tree, plant residues (largest source of biomass energy); biodegradable wastes; alcohol fuels (ethanol)**
- **Treated distinctly from biofuels here**
- **14% of U.S. corn provides 2% of transportation fuel**
- **Renewable source of energy**
- **Currently 1.7 GW of power supplied to the U.S. electricity grid, or about 0.5% of the total, comes from biofuel combustion**
- **3 TW would require the use of 6x1012 m^2 of dry land, while 20 TW would require 1.3x1014 m2 (31% of total land area of earth)**
- **Biomass use is highly scalable**
- **$80-$150/MWh**

Wood chips

Figure A-24. Characteristics of Biomass Fuels.

A.15.1 Summary

We have used biomass energy or “bioenergy”—the energy from plants and plant-derived materials—since people began burning wood to cook food and keep warm. Wood is still the largest biomass energy resource today, but other sources of biomass can also be used. These include food crops, grassy and woody plants, residues from agriculture or forestry, and the organic component of municipal and industrial wastes. Even the fumes from landfills (which consist largely of methane, a natural gas) can be used as a biomass energy source.

Biomass energy supports US agricultural and forest-product industries. The main biomass feedstocks for power are paper mill residue, lumber mill scrap, and municipal waste. For biomass fuels, the feedstocks are corn (for ethanol) and soybeans (for biodiesel), both surplus crops. In the near future, agricultural residues such as corn stover (the stalks, leaves, and husks of the plant) and wheat straw will also be used. Long-term plans include growing and using dedicated energy crops, such as fast-growing trees and grasses, which can grow sustainably on land that will not support intensive food crops.[101]

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101 National Renewable Energy Laboratory, July 2008.

A.15.2 Basic Principles

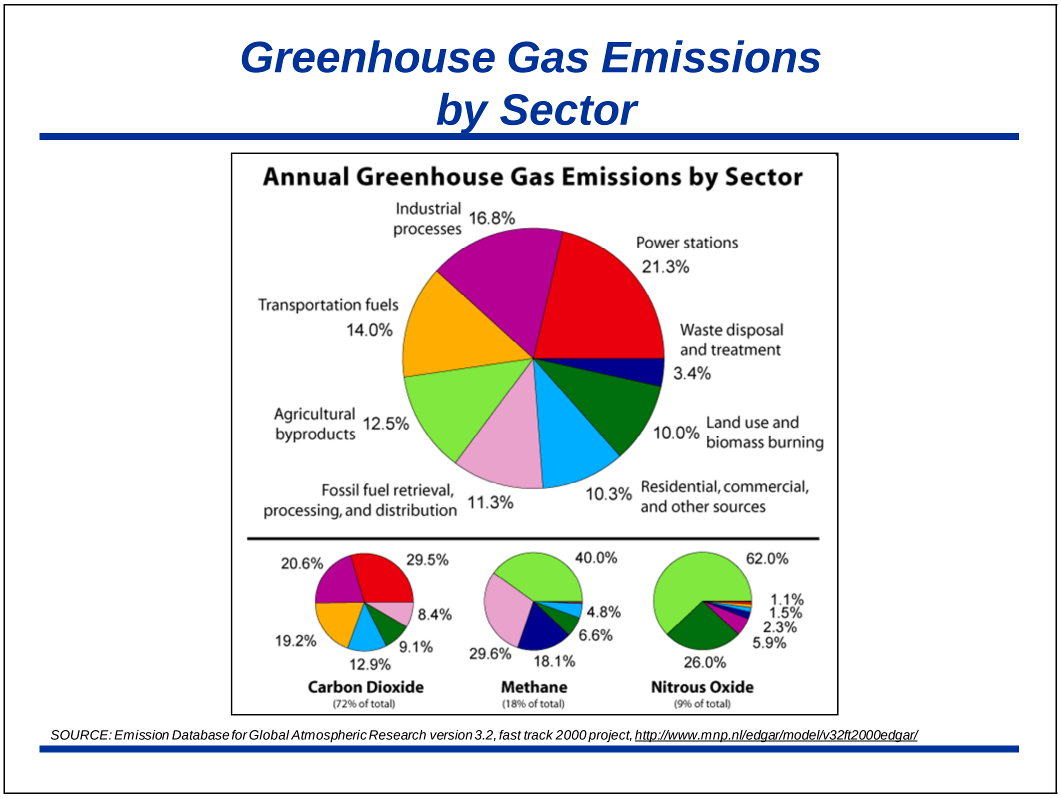

Figure A-25. Sources of Biomass.

Biomass refers to matter derived from biological systems (usually but not exclusively plant matter) that can be used to provide energy. The term "biomass" commonly includes dead tree and plant residues, biodegradable wastes that can be used for fuel, and alcohol fuel (or ethanol). It does not include fossil fuels (oil, coal, natural gas). (Note: biomass as used here is distinct from *biofuels,* which are discussed in Recommendation 3. While both have common sources, "biomass" typically refers to direct consumption of the source for energy, while "biofuels" refers to the product of newer chemical engineering processes that produce more energy-concentrated fuels from biological sources.)

Harvested wood has long been used as a fuel; additional sources for current biofuel usage come from wood waste streams. These together comprise the largest source of biomass energy. The second-largest comes from waste energy, harvested from municipal solid waste, manufacturing waste, and landfill gas. Ethanol is mostly derived from corn, and is primarily used as an oxygenate in gasoline. Currently roughly 14% of all US corn provides 2% of its transportation fuel.

A.15.3 Capabilities and Payoffs

In 2001, the worldwide energy consumption from biomass was 1.24 terawatts (TW), comprising about 10.6% of the total (13.2 TW). US consumption was roughly ¼ of the worldwide amount. Currently only about 1.7 gigawatts (GW) of power supplied to the US electricity grid, or about 0.5% of the total, comes from biofuel combustion.

In 2020 the projected global energy consumption is roughly 20 TW. Use of biomass to provide a significant portion of this will require the setting aside of large land areas due to its inefficiency (0.3%). Three terrawatts would require the use of $6x10^{12}$ m^2 of dry land, while 20 TW would require $1.3x10^{14}$ m^2 (31% of total land area of earth). N. S. Lewis estimates the additional land needed for biomass to support 9 billion people in 2050 is $0.416x10^{13}$ m^2, while the remaining land available for this purpose is $1.28x10^{13}$ m^2.[102] He estimates that instead perhaps 5-7 TW might be available by 2050 through biomass. Land usage for this purpose is likely to be water resource limited.

A.15.4 AF Base Biomass Use

The present model uses dry biomass (wood chips or dry waste) for energy cogeneration. The biomass input is sent to a gasifier, with the resulting fuel sent to a boiler. Most bases now use dual capacity boilers that can burn either natural gas or biomass. Biomass availability is largely concentrated in the northern central states (Illinois, Iowa, Minnesota, and North Dakota) with other pockets along the West Coast, the South, and the northern New England states.[103]

Eglin AFB, in the Florida panhandle, has just completed (November 2009) a feasibility study for options available to convert waste to renewable energy. This five-month, Americans for Responsible Recreational Access-funded study examined all organic waste streams at Eglin AFB, including a study of the extensive fuelwood resources (woody biomass) available in the Northwest Florida region. If it can be performed economically, conversion of this sustainable forest resource to electrical energy would enable Eglin to achieve most of its renewable energy goals, and it would provide added security through an on-site power generation facility. Key aspects in determining economic feasibility are the distance over which the biomass must be transported, and the efficiency of collection.[103]

Biomass use is highly scalable, with a steep cost curve: large plants cost less per energy unit than small plants. A plant of power capacity 5 MBtu (million British thermal-units) per hour will cost roughly $250K/MBtu, while a plant with capacity 25 MBtu/hr is estimated to cost $50K/MBtu.

A.15.5 Concerns and Issues

Biomass is renewable, but its use as an energy source has essentially the same impact on atmospheric carbon dioxide as the burning of fossil fuels. In the year 2000, approximately 10% of worldwide greenhouse gas emissions arose from the burning of fuels derived from biomass.[104] Some groups (e.g., Nature Conservancy) have argued that biomass, rather than being carbon-neutral with respect to fossil fuels, may be even worse: land clearing for the purpose of growing biomass crops would lead to decomposition that would release sequestered CO_2.

On the other hand, those advocating biomass use (e.g., USA Biomass Power Producers Alliance) argue that current burning of biofuels avoids approximately two million tons per year of methane that would otherwise be released into the atmosphere if the biomass were disposed of by burial, spreading, or open burning. Rotting biomass produces a mixture that can be up to 50% methane, while open pit burning releases gases that are up to 10% methane. Controlled

102 Lewis, 2009.
103 Walker, 2009, Renewable Energy Optimization for Air Force Bases.
104 European Commission, 2005.

combustion, on the other hand, releases almost no methane; the waste gas component is mostly CO_2. Consequently, the shift from methane to carbon dioxide significantly reduces the global warming impact in this sector.

A.16 Waste to Energy

A.16.1 Summary

Waste-to-energy (WtE) or energy-from-waste is the process of creating energy in the form of electricity or heat from the incineration or biological degradation of a waste source. WtE is a form of energy recovery. Most WtE processes produce electricity directly through combustion, or produce a combustible fuel commodity, such as methane, methanol, ethanol, or synthetic fuels. In addition to the resources summarized in the Biofuels portion of this Appendix, WtE systems can use wastewater or municipal garbage as feedstocks.

A.16.1.1 Wastewater Energy

One of the most often overlooked sources of energy in the United States today is the potential for energy recovery during waste water treatment. Using combined heat and power (CHP) recovery equipment, significant biogas can be recovered and applied to natural gas applications on bases, in cities, or elsewhere. CHP (Figure A-26 below) is a reliable, cost-effective option for WWTFs that have, or are planning to install, anaerobic digesters. The biogas flow from the digester can be used as "free" fuel to generate electricity and power in a CHP system using a turbine, micro-turbine, fuel cell, or reciprocating engine. The thermal energy produced by the CHP system is then typically used to meet digester heat loads and for space heating. A well-designed CHP system offers many benefits for WWTFs because it:[105]

- Produces power at a cost below retail electricity,
- Displaces purchased fuels for thermal needs,
- Qualifies as a renewable fuel for green power programs,
- Enhances power reliability for the plant, and
- Offers an opportunity to reduce greenhouse gas and other air emissions.

105 United States Environmental Protection Agency, April 2007.

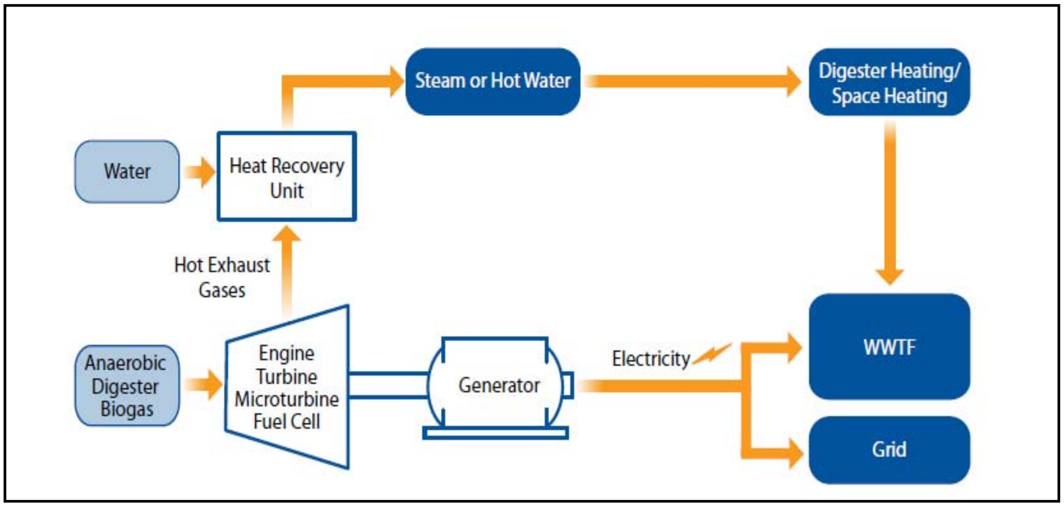

Figure A-26. Combined Heat and Power (CHP) Recovery Derives Both Electric and Heat Energy from Large-Scale Wastewater Treatment.

A.16.1.2 Solid Waste to Energy

Waste water to energy is just one of a number of waste to energy options available today. For example, a recent technology development for deriving energy from primarily solid wastes is plasma treatment. Hurlburt AFB, FL is in the process of installing this new technology, which uses the intense heat of plasmas (10-20 x 10^3 degrees F) to gasify and/or vitrify a waste stream. The gas products include combustible gases like hydrogen, methane, and carbon monoxide. If successful, this technology can reduce landfill problems, provide a low-cost alternative to conventional waste management, and generate electricity and heat (through recovery of energy stored in the waste material).

The system being installed at Hurlburt AFB can handle both hazardous and non-hazardous waste. It is being installed primarily as a solution to the high cost of transportation and disposal of waste at this base, which is currently paying to ship and dispose of its waste out of state. The scale of the project is too small to provide excess energy; it is designed to approximately break even in its energy use.

In its gasification mode, the plasma degradation process does not release carbon dioxide, dioxins, or furans (a toxic heterocyclic organic compound). Because of the extremely high temperatures involved, long chain hydrocarbons (the main constituents of soot and tar) are broken down into carbon monoxide and hydrogen gas. The vitrification process produces an inert slag that can be used for construction; alternatively the elemental components of the slag may be extracted for recycling purposes.

The $6.5M demonstration project was awarded in June 2008 to PyroGenesis Inc., and the demonstration project broke ground in 2009 at Hurlburt Field. The plant is designed to recycle Hurlburt Field's entire waste streams (hazardous, non-hazardous, and medical) in a 10.5 metric ton per day system. The structure will require a total of 5,000 ft^2 not including space required for waste storage, maintenance, control room, and other supporting structures. The Hurlburt project is a technology demonstrator, and the technology is focused on efficient and low-cost waste disposal, rather than cost-effective energy generation. If successful, it will represent an excellent effort at energy conservation and cost reduction, and it may pave the way for larger scale

systems that can be net generators of energy. The subsequent discussion focuses on wastewater energy systems, which are more mature and capable of generating significant quantities of energy.

A.16.2 Basic Principles

For systems designed to recover energy from wastewater, CHP recovery is focused on facilities with anaerobic digesters because anaerobic digesters produce biogas as they break down solids in the waste stream. This generates a form of "free" fuel as a by-product of the waste water treatment. In addition the anaerobic digesters also require heat that a CHP system can meet. CHP requires a certain influent flow rate in order to produce gas and heat at sufficient rates to be economically feasible for WWTFs. The minimum flow rate for WWTFs included in the analysis is 5 million gallons per day (MGD), which is based on previous analyses performed by the Environmental Protection Agency that showed that WWTFs with influent flow rates less than 5 MGD could not produce enough biogas from anaerobic digestion of biosolids to make CHP technically and economically feasible.

A.16.3 Capabilities and Payoffs

Some of the basic data of these systems are given as:

- A typical WWTF processes 100 gallons per day of wastewater for every person served.[106]
- Approximately 1.0 cubic foot (ft^3) of digester gas can be produced by an anaerobic digester per person per day.[107] This volume of gas can provide approximately 2.2 Watts of power generation. (This assumes the energy content of biogas is 600 Btu/ft^3, and the power is produced using a 30 percent efficient electric generator.)
- The heating value of the biogas produced by anaerobic digesters is approximately 600 Btu/ft^3.[108]
- For each 4.5 MGD processed by a WWTF with anaerobic digestion, the generated biogas can produce approximately 100 kilowatts (kW) of electricity.

A well designed CHP system can be an attractive investment for a WWTF. A CHP system allows a WWTF to generate both electric and thermal energy on-site, offsetting the costs of grid power and purchased fuel. To highlight the cost savings of generating energy with a CHP system at a WWTF, the Combined Heat and Power Partnership estimated the cost-effectiveness of three representative CHP systems that would be appropriate for different size WWTFs:

- 130 kW microturbine
- 300 kW carbonate fuel cell
- 1,060 kW reciprocating engine

Each WWTF considering CHP will need to perform its own site-specific feasibility analysis to determine potential biogas generation rates; methods to compress, clean, and dry the

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106 Great Lakes-Upper Mississippi Board of State and Provincial Public Health and Environmental Managers, 2004.
107 Tchobanoglous & Burton, 1991.
108 *Ibid.*

biogas before combustion; and the specific costs and benefits of generating onsite heat and electricity for their WWTF.

A.16.4 Concerns and Issues

The sources of waste water for treatment plants include agricultural drainage water, waste treatment plants, gray water, and industrial effluence. Invariably, most of the water treatment technologies necessary to reclaim water are energy intensive. Increasing salinity of river water, underground reservoirs, irrigation water runoffs, and possibility of use of seawater all require energy intensive technologies.[109]

In addition to producing heat and power form waste energy, CHP Systems are becoming available for homeowners as well. Once available only to large commercial buildings, CHP generation systems are now being produced on a scale that is safe, practical, and affordable to homeowners. CHP technologies (sometimes referred to as cogeneration) have provided heat and electrical energy efficiently at commercial and industrial sites for many years. However, after hundreds of successful residential installations in Japan and Europe, several manufacturers are now offering models in the United States.

A CHP system uses fuel such as natural gas to produce heat and electricity simultaneously. The electricity can be used for any household device such as lights and appliances. Simultaneously, the heat produced can be used for water heating and/or space heating. About 10% of the fuel used is lost as exhaust, much like a high efficiency furnace.

The engines used in the CHP units for producing electricity can be internal combustion or Stirling (also called external combustion) engines. Other types of generation technologies, such as fuel cells, have not reached the commercialization stage. Micro-CHP (as residential-sized CHP systems are usually called) run on propane, natural gas, or even (in the case of Stirling engines) concentrated solar energy or biomass. The byproduct of electricity generation is waste heat—and plenty of it. One 6-kW unit provides 10 gallons per minute of hot water at 140 to 150° Fahrenheit. This waste heat can be used to heat an entire home, water for domestic use, for swimming pools and spas, or even as an energy source for heat-driven (absorption) cooling systems.

CHP systems are extremely efficient, offering combined heat and power generating efficiency of about 90%, compared to about 30 to 40% for electricity from a central power station.

Micro-CHP units range in capacity from about 1 kW to 6 kW and are about the size of a major appliance. Installation may be performed initially by specialists and, after the technology matures, by an experienced plumber, electrician, or HVAC (heating, ventilation, and air conditioning) technician. Units come as grid-tied systems which connect to utility power as backup or as stand-alone systems for remote residences.

109 The California Energy Commission, 2008.

A.17 Landfill Gas

A.17.1 Summary

Methane emissions from landfills represent a lost opportunity to capture and use a significant energy resource. Landfill gas (LFG) is created as solid waste decomposes in a landfill. This gas consists of about 50 percent methane (CH_4), the primary component of natural gas, about 50 percent CO_2, and a small amount of non-methane organic compounds. Municipal solid waste landfills are the second largest source of human-related methane emissions in the United States, accounting for approximately 23 percent of these emissions in 2007 (Figure A-27 below).

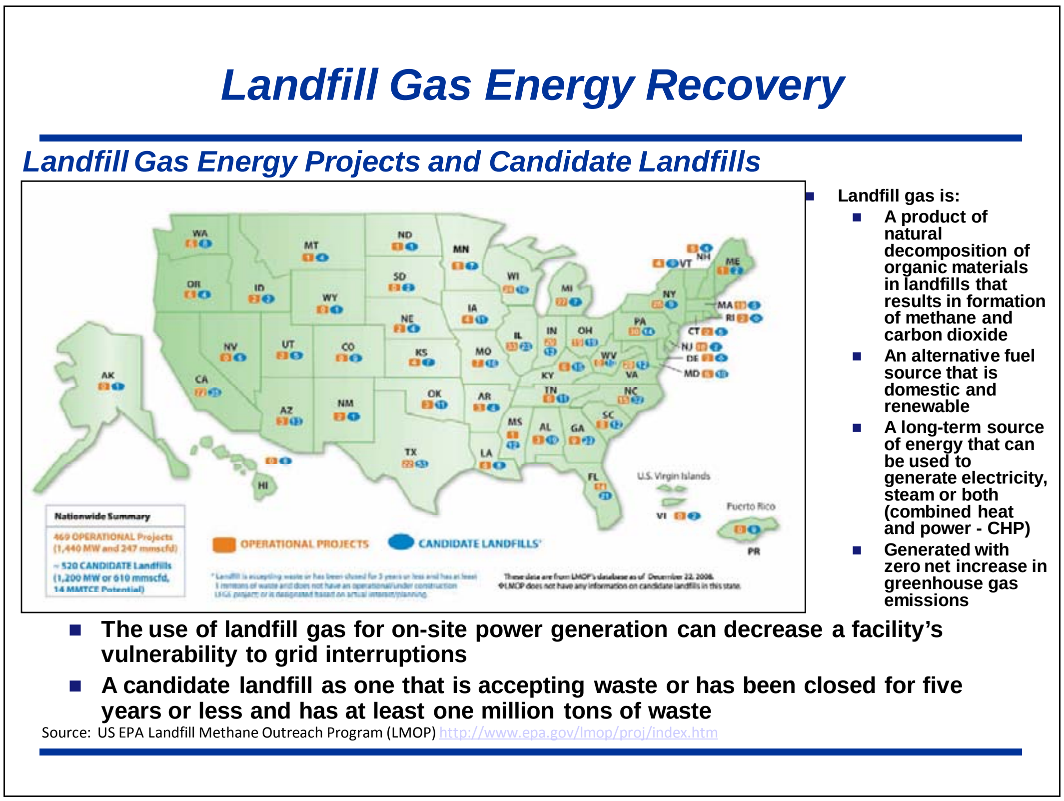

Figure A-27. Distribution of Landfill Gas Energy Recovery Projects and Key Attributes of Landfill Gas Generation of Electricity.[110]

A.17.2 Basic Principles

Instead of allowing LFG to escape into the air, it can be captured, converted, and used as an energy source. Using LFG helps to reduce odors and other hazards associated with LFG emissions, and it helps prevent methane from migrating into the atmosphere and contributing to local smog and global climate change.

Landfill gas is extracted from landfills using a series of wells and a blower/flare (or vacuum) system. This system directs the collected gas to a central point where it can be

110 United States Environmental Protection Agency, 2009.

processed and treated depending upon the ultimate use for the gas. From this point, the gas can be simply flared or used to generate electricity, replace fossil fuels in industrial and manufacturing operations, fuel greenhouse operations, or be upgraded to pipeline quality gas.

A.17.3 Capabilities and Payoffs

The generation of electricity from LFG makes up about two-thirds of the currently operational projects in the United States. Electricity for on-site use or sale to the grid can be generated using a variety of different technologies, including internal combustion engines, turbines, microturbines, Stirling engines (external combustion engine), Organic Rankine Cycle engines, and fuel cells. The vast majority of projects use internal combustion (reciprocating) engines or turbines, with microturbine technology being used at smaller landfills and in niche applications. Certain technologies such as the Stirling and Organic Rankine Cycle engines and fuel cells are still in the development phase.

Directly using LFG to offset the use of another fuel (natural gas, coal, or fuel oil) is occurring in about one-third of the currently operational projects. This direct use of LFG can be in a boiler, dryer, kiln, greenhouse, or other thermal applications. It can also be used directly to evaporate leachate. Innovative direct uses include firing pottery and glass blowing kilns; powering and heating greenhouses and an ice rink; and heating water for an aquaculture (fish farming) operation. Current industries using LFG include auto manufacturing, chemical production, food processing, pharmaceutical, cement and brick manufacturing, wastewater treatment, consumer electronics and products, paper and steel production, and prisons and hospitals, to name just a few.

Cogeneration (also known as combined heat and power or CHP) projects using LFG generate both electricity and thermal energy, usually in the form of steam or hot water. Several cogeneration projects have been installed at industrial operations, using both engines and turbines. The efficiency gains of capturing the thermal energy in addition to electricity generation can make these projects very attractive.

Production of alternate fuels from LFG is an emerging area. Landfill gas has been successfully delivered to the natural gas pipeline system as both a high-Btu and medium-Btu fuel. Landfill gas has also been converted to vehicle fuel in the form of compressed natural gas and liquefied natural gas. Projects to convert LFG to methanol are in the planning stages.

Using LFG for energy is a win/win opportunity. Landfill gas utilization projects involve citizens, non-profit organizations, local governments, and industry in sustainable community planning and create partnerships. These projects go hand-in-hand with community and corporate commitments to cleaner air, renewable energy, economic development, improved public welfare and safety, and reductions in greenhouse (global warming) gases. By linking communities with innovative ways to deal with their LFG, the Landfill Methane Outreach Program contributes to the creation of livable communities that enjoy increased environmental protection, better waste management, and responsible community planning.

A.17.4 Concerns and Issues

Landfill gas is about 40-60% methane, with the remainder being mostly CO_2. Landfill gas also contains varying amounts of nitrogen, oxygen, water vapor, sulfur and a hundreds of other contaminants—most of which are known as "non-methane organic compounds" or

NMOCs. Inorganic contaminants like mercury are also known to be present in landfill gas. Sometimes, even radioactive contaminants such as tritium (radioactive hydrogen) have been found in landfill gas.

NMOCs usually make up less than 1% of landfill gas. The Environmental Protection Agency identifies 94 NMOCs in their 1991 report, "Air Emissions from Municipal Solid Waste Landfills - Background Information for Proposed Standards and Guidelines." Many of these are toxic chemicals like benzene, toluene, chloroform, vinyl chloride, carbon tetrachloride, and 1,1,1 trichloroethane. At least 41 of these are halogenated compounds. Many others are non-halogenated toxic chemicals.[111]

Burning landfill gas is dirtier than burning natural gas. Whether using an internal combustion engine or a gas turbine, burning landfill gas to produce energy emits more pollution per kilowatt hour produced than the burning of natural gas.[112]

A.18 Hydroelectric Energy

A.18.1 Summary

Hydroelectric energy generation provides a method for creating electricity from a renewable resource, while generating very little pollution. The first hydroelectric power station in history started producing electricity in 1882. It was located in the state of Wisconsin, and used the Fox River for electrical generation. China now claims to generate more hydroelectricity than any other country, and it has built hydropower stations in other countries as well.[113] In the United States, hydropower is used to produce more electricity than all other renewable electricity generation methods combined.[114]

A.18.2 Basic Principles

Hydroelectric power plants generate electricity by turning a turbine—converting the potential energy of confined water into kinetic energy imparted to the turbine, which in turn produces electrical energy by spinning an electric generator. Transformers convert the electricity into a transmittable and usable form.[115]

111 United States Environmental Protection Agency, 1991 and United States Department of Energy: Growth of the Landfill Gas Industry, 1997.
112 United States Environmental Protection Agency, 1995.
113 China Daily, 2004.
114 United States Department of Energy: Hydropower, 2007.
115 United States Department of the Interior, 2009, and Bonsor, 2001.

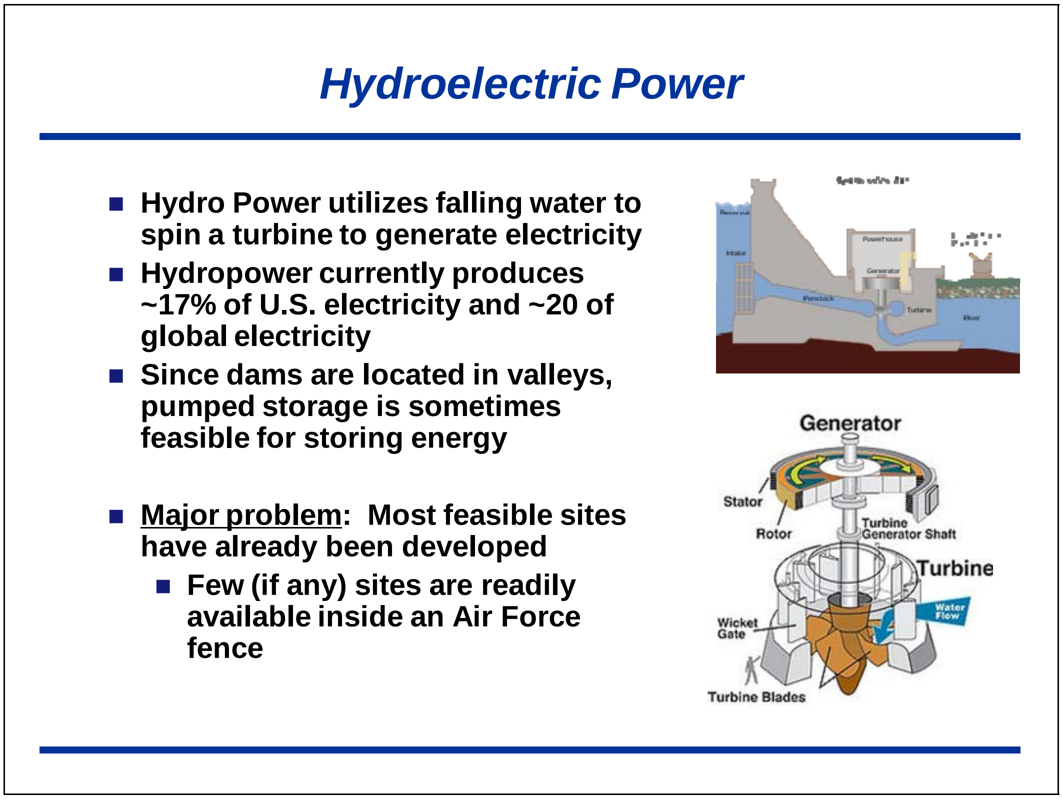

Figure A-28. Summary of Key Information on Hydroelectric Power Plants.

A.18.3 Capabilities and Payoffs

Hydroelectric power plants are capable of functioning with low Operation and Maintenance costs for long periods of time. For example, according to Natural Resources Canada,[116] a large number of Canadian hydropower stations have been in use for more than 50 years. Hydroelectric plants produce renewable, clean, non-polluting electric energy. However, the ability to locate such a plant on or near an Air Force base is highly geography-dependent.

A.18.4 Concerns and Issues

Hydropower is a large, but limited resource. Most of the US hydroelectric resource is already exploited, and the potential for a hydroelectric project is often limited by environmental concerns—impacts on species that live on the land that is to be flooded, destruction of the land around the dam, and turbines that can kill the smallest fish even if the water collection chutes are screened.

A.19 Conservation Technologies

A.19.1 Buildings

Buildings use about 40% of the nation's energy and about two-thirds of its electricity. Building climate control, lighting, and appliances all present opportunities to reduce energy

116 Natural Resources Canada, 2009.

consumption. The Air Force has been aggressively pursuing conservation efforts on all of its CONUS Bases.

A.19.1.1 Climate Control

The construction of new buildings certified to Leadership in Energy and Environmental Design (LEED) standards, created by the US Green Building Council, provides energy savings of typically 25-30%. Improved insulation, glazing, HVAC systems, and smart controls all can contribute to conserving energy. These technologies can also be implemented as retrofits to existing buildings. Residents can assist in climate control by closing shades and drapes when it is desired not to allow cool exterior conditions to cool the building or hot exterior conditions to heat the building. Opening shades and drapes also will allow heat to flow in the opposite direction when desired. Some buildings have automatic blinds to perform this function.

A.19.1.2 Lighting

The incorporation of passive daylighting, in which solar lighting provides substantial inside illumination during daylight hours, into new building designs or as a retrofit into established structures is becoming common throughout the world. Daylighting systems can be simple windows (often double- or triple-paned to avoid heat losses), skylights, or more complex "light or solar pipes." Retrofitting skylights into large structures such as warehouses or hangars seems like an easy and cost-effective procedure, although the Panel heard several anecdotal reports from civil engineering groups within the Air Force that such projects have produced significant water leaks that have been much more costly to fix than the energy savings they incurred. Whereas skylight technology has matured significantly from the original "plastic bubble" technology of the 1970s, the improper installation of skylights into buildings which were not designed for skylights can still lead to problems. The perceived risk of leaks has inhibited the more widespread installation of skylights in Air Force buildings.

The efficiency of lighting is improving rapidly. Compact fluorescent lights (CFL) use 70% less energy than incandescent bulbs, and white light-emitting diode (LED) lights use up to 90% less. The Energy Independence Security Act of 2007 calls the Secretary of Energy to plan for a phase-out of incandescent bulbs in most applications. Current LED technology is too expensive compared with CFL, although a new generation of LEDs are expected to provide even more efficient lighting and at lower cost.[117] The main drawback with CFL lighting is that the bulbs use mercury and so inappropriate disposal creates an environmental hazard. While LEDs use some toxic materials, primarily metalloids, they are more easily recovered and less likely to leak from a discarded device than is the mercury from CFLs. The Panel's opinion is that CFL will continue to be the lighting of choice in the near-term, but the rapid evolution of LED lighting technology will almost certainly replace CFL in the near- to mid-term. The reason for this is that the primary limit to the cost of LED technology is the cost of manufacturing rather than the cost of the raw materials.

Apart from the lower power drain for a given light level that the new technologies deliver, adjusting lighting level according to need provides an opportunity to deliver substantial energy reduction. This includes the automatic monitoring of room occupancy, and modification of accepted behavior patterns (turning out the lights when one leaves the room, turning off computers and printers at the end of the day, etc.).

117 Wang et. al., 2009. See also Goode, 2009.

A.19.1.3 Appliances

The big users of energy in buildings are furnaces, air conditioners, refrigerators, washers, dryers, dishwashers, hot water heaters, television, and office equipment (e.g., computers, printers, copiers, shredders).

A.19.1.4 Furnaces

Natural gas furnaces, where natural gas is available, are generally more economical to run than electric heating. Older natural gas furnaces, both forced air and hot water, have efficiencies of about 65%. The minimum allowed efficiency of current forced air gas furnaces is 78%. The best units, which have spark ignition systems and use the combustion products (including condensing water vapor) to heat the incoming air, have efficiencies of up to 97%.

A.19.1.5 Air Conditioners

Air conditioners transfer heat from inside air to outside air to produce summer cooling. They operate functionally the same as refrigerators and similarly benefit greatly from having good insulation between the cool interior and hot exterior. New units benefit from substantially higher efficiencies, requiring about half the energy of units of 30 years ago.

A.19.1.6 Heat Pumps

Air source heat pumps run on electricity and transfer heat efficiently from outside air to the house (heating) or from the house to outside air (cooling). (Note: Air conditioners are heat pumps that operate in a cooling mode only.) They work best for heating in climates where the outside air is not below 40^{o}F for long periods. Geothermal heat pumps transfer heat from or to a nearly constant temperature underground source, yielding higher efficiencies than air source heat pumps and operating efficiently even at low ambient air temperatures. They have the advantage of having sink temperatures that are lower than the air temperature during the summer and warmer than the air temperature during winter. Their disadvantage lies in the high cost of drilling the geothermal heat exchanger. Where a water reservoir is available, water source heat pumps are possible. Heat pumps can also provide hot water.

A.19.1.7 Refrigerators

The efficiency of refrigerators has increased dramatically over the past 30 years, reducing energy consumption by more than 75% while capacity has increased.

A.19.1.8 Washers, Dryers, Dishwashers

Efficiency improvements of these devices haves been less dramatic than refrigerators and have less opportunity for large increases in efficiency. Energy use can be reduced substantially through reducing hot temperatures or using cold washing cycles (in washers). Delaying use until the unit is full also is an effective energy conservation measure.

A.19.1.9 Television (TV)

Large screen television increased energy consumption, with plasma TVs consuming more energy than LED TVs. The "ready" mode of operation places a constant power drain on most entertainment devices. This can be reduced by accepting a delay in turn-on times.

A.19.1.10 Office Equipment (Computers, Printers, Copiers, Shredders)

The widespread use of computers, including at large server installations, creates a large power demand, prompting measures to reduce energy consumption. The problem is compounded by air conditioning requirements at large installations. Most of these devices have a ready mode of operation or, as in the case of computers, are left on while not in use. Both technological (automatic and full turn-off) and behavior (manual turn-off when not in use) approaches to reducing energy consumption exist.

A.19.2 Infrastructure

Base infrastructure and its operation provide additional opportunities for energy conservation. Improvements to street lighting include both lamp technology and techniques for directing light to roads. Light emission diode traffic lights are common in the public sector. Electric motor efficiency has substantially increased in recent years and provides an opportunity to reduce energy in water and sewer pumping.

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Appendix B: Energy Storage Technologies

Relevant to Recommendation 3

B.1 Energy Storage Summary

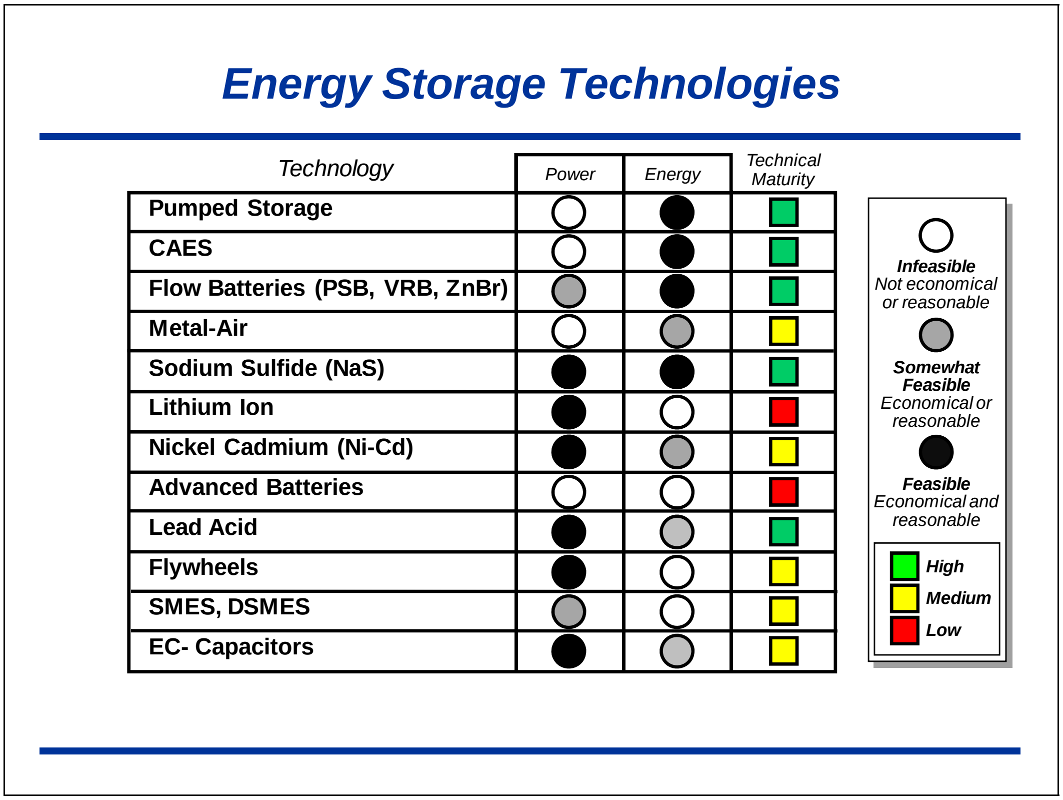


Figure B-1. Comparison of Energy Storage Options.[118]

There are a variety of energy storage options that are applicable to power applications of the scale necessary to support the renewable energy systems considered in this study. A summary is provided in Figure B-1 above, which lists the primary advantages of the specific system, its primary disadvantages or limitations, its application to power needs (those needs that require instantaneous restoration of a specified amount of electric power) and its application to energy needs (those needs that require the power level be maintained for some time). Power is defined as energy per unit time, and so which parameter is more important depends on the type of electricity function being supported. For example, to support a transient outage in the grid that may last for only a fraction of a second, power is the key parameter. For a longer term outage (minutes to days), energy is the parameter that determines if the storage option will be able to maintain the required power level throughout the outage. For a renewable energy system such as solar photovoltaic (PV) to provide stand-alone power for a facility, the energy capacity

118 Data obtained from Electricity Storage Association: Technologies, 2009.

of the storage system must be sized to allow for eight or more hours of zero output from the PV system. The table is laid out such that it starts with those technologies focused on energy restoration and shifts to those technologies that are focused on power restoration. An excellent, in-depth market analysis and technology description of the electricity storage options relevant to alternative energy projects on Air Force Bases is available.[119]

The efficiency of these storage systems is depicted in Figure B-2 below in terms of returned energy out for a given energy input. The costs of the systems are shown as a function of power or energy capacity in Figure B-3.

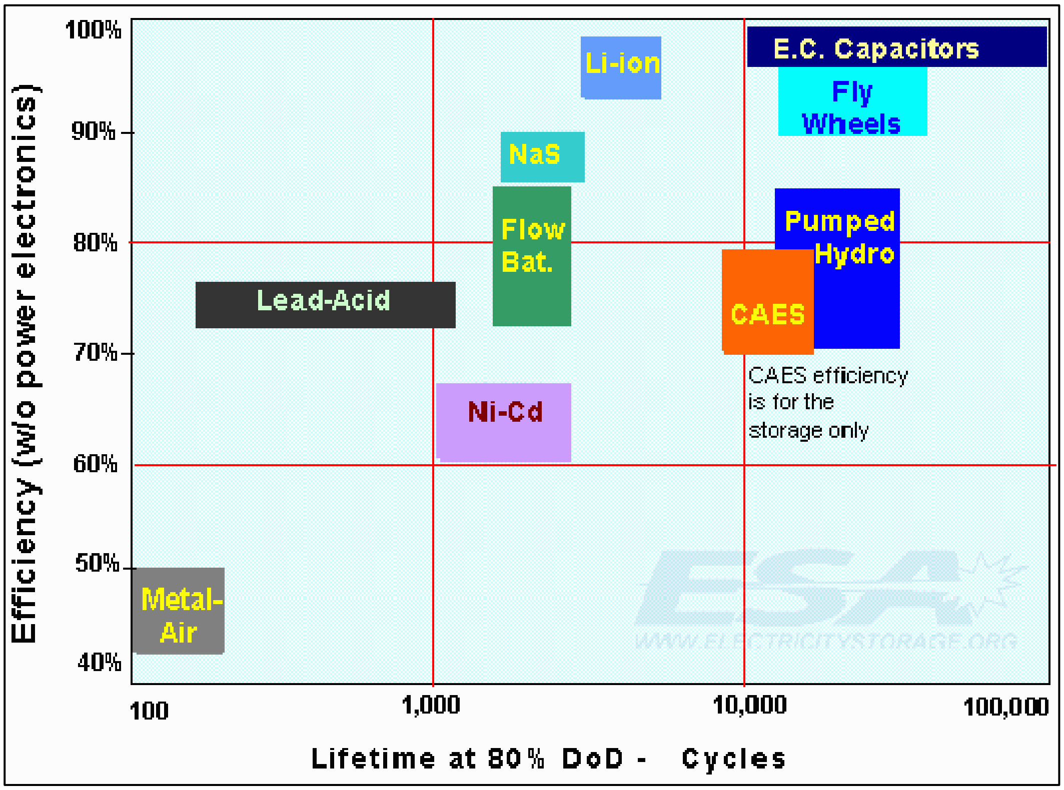
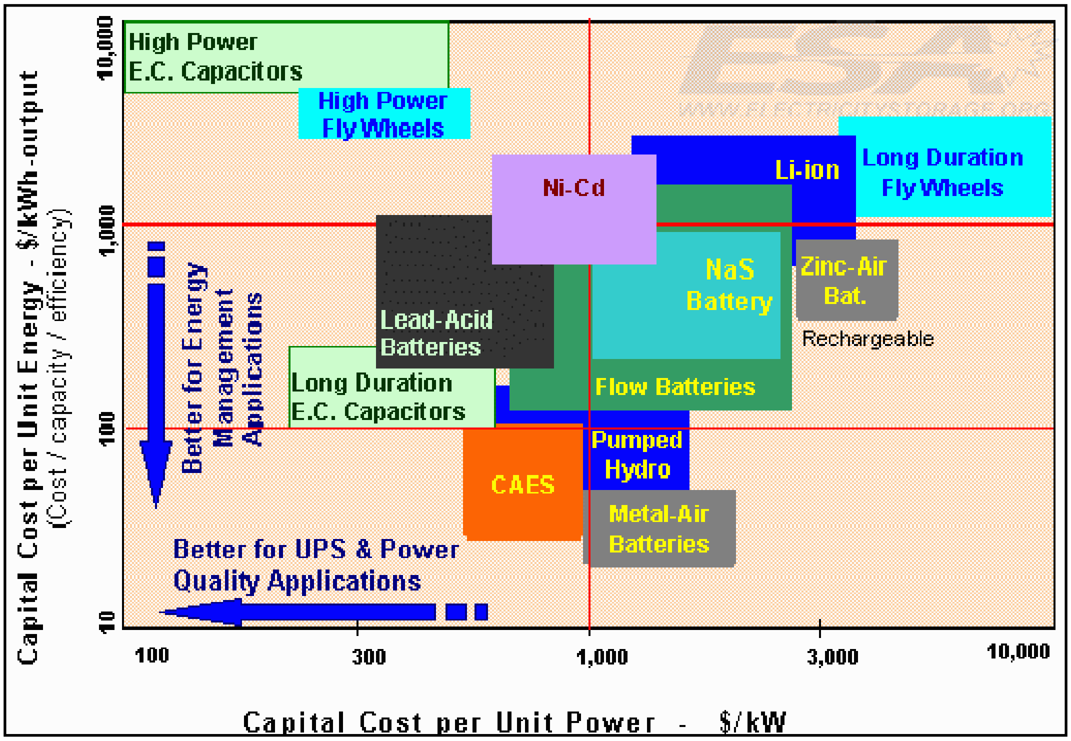


Figure B-2. Efficiency of Several Energy Storage Systems. Note: Data from the Electricity Storage Association (ESA).[120]

The top chart of Figure B-3 (below) compares capital cost per unit energy vs. capital cost per unit power, providing ranges for uncertainties, while the bottom chart provides a simple cost estimate per kilowatt (kW) of power stored. Note that CAES (Compressed Air Energy Storage) does not include the fuel cost for the discharge cycle. "Advanced CAES" represents energy storage by means of compressed air alone, without combustion of a fuel. Note the discrepancy in estimates for Sodium-Sulfur (NaS) versus Lithium-ion batteries. The lower plot considers Li-ion as a shorter-term, smaller capacity storage medium (for frequency regulation rather than for long-duration power storage).

119 Walawalkar & Apt, 2008.
120 *Ibid.*



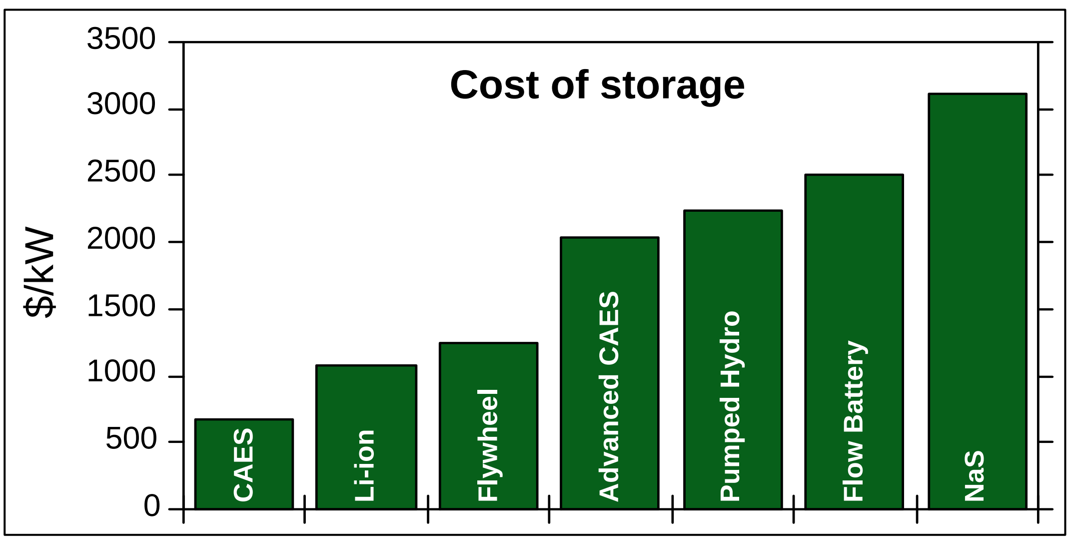


Figure B-3. Costs of Several Energy Storage Systems, Estimated by ESA (Top) [121] *and by EAC (Bottom).*[122]

Many electric energy storage alternatives are available today, ranging from short-term power delivery devices, most useful for backup power and leveling out short term interruptions, to long-term high-energy storage systems that can provide gigawatts of power during long-term power generation outages. Between these extremes is a continuum of different technologies capable of bridging power losses for short periods of time up to base-level operations for several hours. Each of the systems has its own niche applications. For example, rechargeable

121 *Ibid.*
122 United States Electricity Advisory Committee, 2008.

nickel-cadmium or other metal-based batteries power computers and servers during short term power outages. Pumped hydro systems provide reliable long-term energy for regional power grids whenever demand is high.

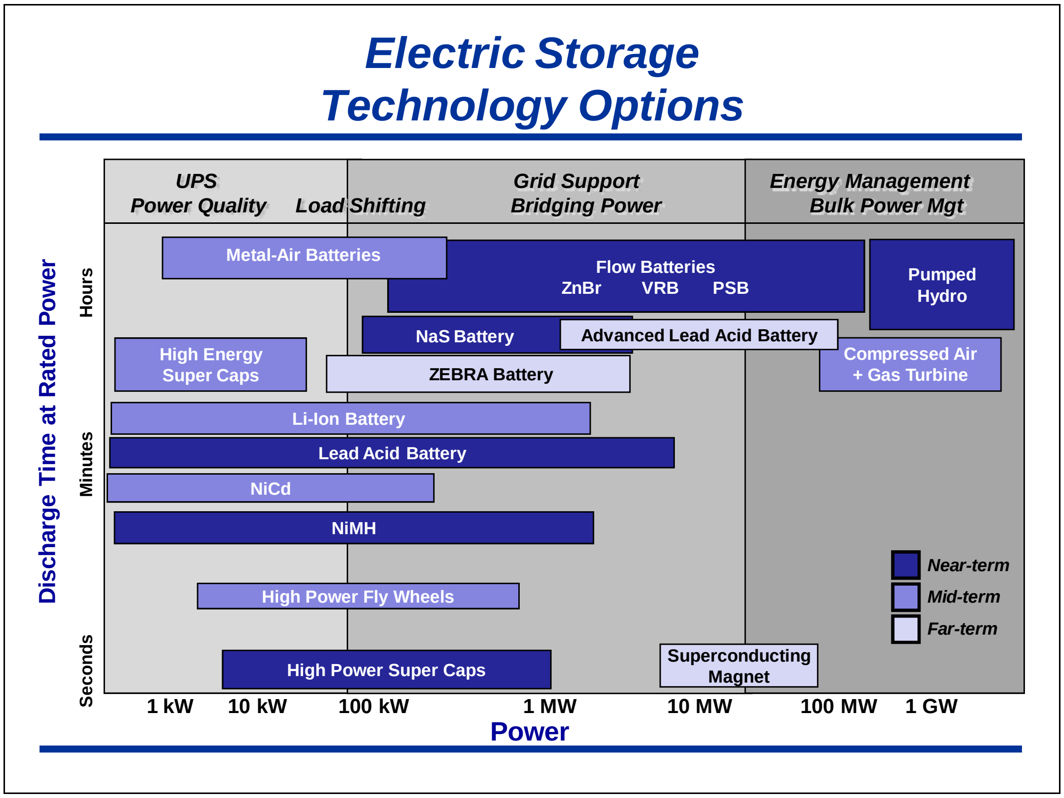


Figure B-4. Comparison of Electric Storage Technology Options.

There are large, international investments in all of the storage technologies depicted above. The Air Force maintains a robust Science and Technology presence in rapid discharge, high energy density capacitors needed for pulsed power applications such as Directed Energy weapons. Apart from this investment, and the energy-to-liquid fuels problem described below, the Panel does not recommend that the Air Force invest in research into new energy storage technologies. However, it does recommend that the Air Force carefully monitor and harvest relevant advances as they become available. The following discussion outlines concepts aimed at providing power to Air Force bases for both short-term interruptions and longer term power outages until local grid power generation systems can be restored. Systems that provide power in the 100 kW to 40 megawatt (MW) range for time periods of minutes to hours to days are of most interest. These systems can serve dual purposes: power bridging for alternative energy systems that have intermittent, under-, or over-production periods (like wind, solar, etc,); and covering a major regional outage occurrence.

For longer outages (hours or days), the Panel finds that liquid fuel-powered turbine generation systems are attractive for the reasons discussed in the following section. However, to bridge or manage power output from alternative energy systems appropriate battery back-up systems could be an integral part of a micro-grid base system.

For many short-term power needs, batteries provide the most obvious, currently available solution. They are very efficient storage media, with efficiencies as high as 90%, but they suffer from the fact that they exhibit a finite number of charge/discharge cycles. Crude lifetime estimates, derived from secondary sources, are given in the references.

B.2 "Wet" Batteries

In the near-term, "wet-batteries" such as lead-acid (automotive) batteries and sodium-sulfur batteries provide a potentially cost-effective MW-class storage solution. Examples of deployment of these technologies can be found in Japan and in the United States.

B.2.1 Lead Acid Battery

Lead-acid batteries are comprised of metallic lead and lead oxide electrodes submerged in a sulphuric acid electrolyte. Lead-acid is one of the oldest and most developed battery technologies, a low-cost and popular storage choice for power quality, uninterruptible power supply, and some spinning reserve applications. While the energy density is relatively low, the power density and ability to handle high surge currents make them a viable option.

B.2.2 Sodium-Sulfur Batteries

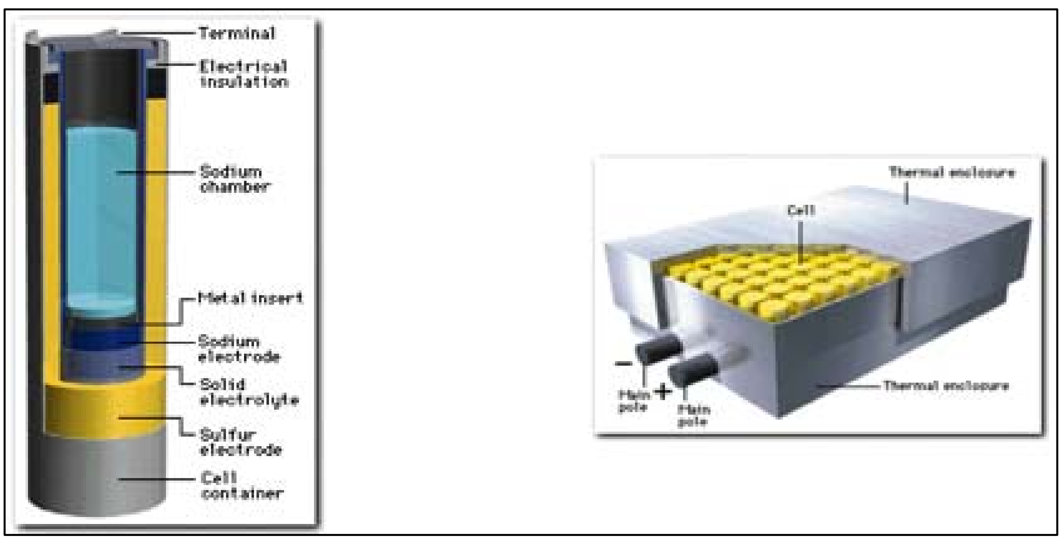


Figure B-5. Sodium-Sulfur Batteries and Ganging Within a Thermal Enclosure to Increase Energy Storage Capacity.[123]

Sodium-sulfur batteries are high-temperature batteries that operate above 250 degrees Centigrade (C) and utilize molten materials to serve as the positive and negative elements of the battery. This chemistry produces battery systems with very high power densities, high discharge rates, and it can be scaled to large (MW-class) systems. The technology is sufficiently mature that it has been demonstrated at this scale.[124] Another high temperature battery commonly used

123 Electric Storage Association: NaS Batteries, 2009.
124 Appalachian Power, 2006.

in this class is the sodium nickel chloride (NaNiCl) battery. Figure B-5 above shows a diagram of a sodium-sulfide battery and a bank of batteries that can produce greater power. Figure B-6 below describes the use of a large bank of sodium sulfide batteries to bridge peak needs for a commercial power provider.

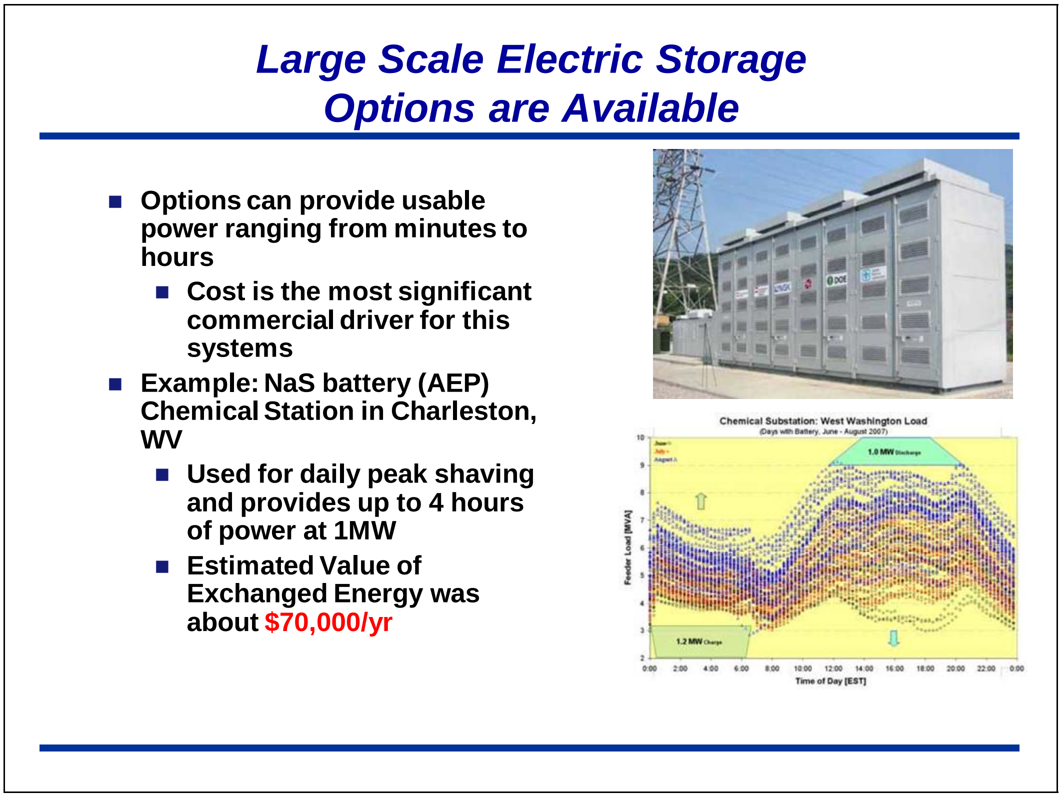


Figure B-6. Sodium-Sulfur Batteries Have Been Used for Large-Scale Power Bridging. (The image in the upper right shows an example of an NaS battery installed at the American Electric Power Chemical Station in Charleston, WV. The battery is used for daily peak shaving. The estimated value of exchanged energy for this battery was ~$70,000/yr in 2008. The alternating current (AC) efficiency of charging and discharging is 80%, although because the battery is located closer to the load center, the efficiency is effectively 90% considering the losses that would be incurred if the peak load had to be supplied by the transmission and distribution grid.[125])

B.2.2.1 Basic Principles

A sodium-sulfur battery consists of liquid (molten) sulfur (S) at the positive electrode and liquid (molten) sodium at the negative electrode as the active materials. They are separated by a solid beta alumina ceramic electrolyte. The electrolyte allows only the positive sodium ions to pass through it and combine with the sulfur to form sodium polysulfides. During discharge, positive sodium (Na^+) ions flow through the electrolyte and electrons flow through the external circuit, producing about 2 volts. This process is reversible, as charging causes sodium

125 Nourai et. al., 2008.

polysulfides to release the positive sodium ions back through the electrolyte to recombine as elemental sodium. The battery operates at 300 °C due to the low rate of diffusion of Na^+ through beta alumina at lower temperatures. NaS battery cells have a cycle efficiency of ~89%.[126]

B.2.2.2 Benefits and Payoffs

Large utility-scale use of NaS batteries has been demonstrated, and several examples are given below to highlight the benefits and payoff of the technology. In all of these examples, some characteristic drivers become apparent: the lack of available transmission capability; the financial incentive of accessing power during off-peak rate periods; or the unavailability of space or resources to install less expensive alternatives such as pumped hydro.

In late 2008, Xcel Energy, in partnership with the University of Minnesota, the National Renewable Energy Laboratory, and the Great Plains Institute, commissioned and energized a one-megawatt sodium-sulfur battery storage system that stores wind energy and dispatches it to the electricity grid when needed. The system has been (2008-2009) undergoing evaluation testing involving multiple modes of operation for the battery, and the collection of data reflecting seasonal, weekly, and daily variations in operating conditions expected to be encountered over the course of a typical year.[127]

Fully charged, the batteries could power 500 homes for six and one-half hours. Xcel Energy will purchase the batteries from NGK Insulators, Ltd. The sodium-sulfur battery is commercially available and versions of this technology are already being used in Japan and in a few US applications, but this will be the first US application of the battery as a direct wind energy storage device.

As of May, 2009, NGK had installed a sodium-sulfur battery system of 34 MW capacity at a 51 MW wind farm project in Japan (developed by Japan Wind Development Company, JWD), a 1.5 MW capacity system serving a 5 MW solar PV array in Hokkaido, the 1 MW system serving a wind farm developed by Xcel Energy described above, and two peak shaving systems in the United States.[128] The 34 MW system in operation for JWD represents the largest wind-NaS battery integration project to date.

One of the NGK peak shaving systems was delivered to Appalachian Power in 2006. The 1.2 MW system was the first megawatt-class NaS battery to be installed in North America (Figure B-6 above). This advanced energy storage technology is intended to ensure a reliable supply of electricity for customers in and around Charleston, and it allowed Appalachian Power to defer an otherwise larger upgrade to help keep overall costs low.[129] The 50-kilowatt (kW) battery modules, 20 in total, are roughly the size of two semi trailers and weigh approximately 60 tons. They store 6.5 megawatt-hours of electricity, with a charge/discharge capacity of one megawatt.

B.2.2.3 Concerns and Issues

The main issue with NaS, as with all battery storage systems, is cost. When the grid does not have the capacity to handle the peak output of a wind or solar project, a battery system can be

126 NGK Insulators, LTD., 2009, and Electricity Storage Association, 2009.
127 Novachek, 2009.
128 NGK Insulators LTD., 2009.
129 Appalachian Power, 2006, and Kasey, 2007.

less expensive than a grid upgrade. The requirement for the battery to operate at high temperature can limit efficiency if the system is needed only periodically. If allowed to cool, the load-following capabilities are significantly compromised (time is required to re-heat the electrolyte to operating temperature). Nevertheless, NaS is currently a leading technology in the area of high power storage.

B.3 Flow Batteries

Flow battery technology utilizes an active element in a liquid electrolyte that is pumped through a membrane similar to a fuel cell to produce an electrical current. These include zinc-bromide (ZnBr), vanadium redox batteries (VRB), and polysulfide-bromide (PSB) systems are under development.[130] Rechargeable flow batteries suitable for high power storage applications are being proven in the field and they may soon be more widely available. Vanadium redox flow batteries are currently installed at Huxley Hill Wind Farm in Australia, Tomari Wind Hills at Hokkaidō, Japan, and there are other non-wind farm applications. A 12 MW-hour (MWh) flow battery is soon to be installed at the Sorne Hill wind farm in Ireland.[131] As previously described, these storage systems are designed to smooth out transient fluctuations in wind energy production.

A flow battery (Figure B-7 below) is a special type of rechargeable battery in which the reactants that produce electrical current are in a liquid form. This is in contrast to a conventional rechargeable battery in which the reactants are in solid form (e.g., lead/lead oxide in a lead-acid battery). Because the active reactants are liquid, they can be stored external to the electrochemical cell, allowing scale up of power and capacity. In addition, external storage of reactants avoids self-discharge that is observed in primary and secondary battery systems.[132] In a flow battery some of the electrolyte (generally the majority in terms of weight and volume) flows through the reactor. This differs from a fuel cell in which the electrolyte remains at all times within the reactor (in the form of an ion-exchange membrane, for example). What flows into a fuel cell reactor are only the electroactive chemicals (e.g., hydrogen, methanol, oxygen, etc.).

Flow batteries are also distinguished from fuel cells by the fact that the chemical reaction involved is often reversible, (i.e., they are generally of the secondary battery type and so they can be recharged without replacing the electro-active material). Also, an important factor in a flow battery is that the power and energy density of the flow batteries are independent of each other in contrast to rechargeable secondary batteries.

There are several electrochemical technologies being used for back-up technologies. These include zinc-bromine (ZnBr), VRB, and PSB.

130 Bartolozzi, 1989.
131 Kuntz & Dawe, 2005.
132 Bartolozzi, 1989.

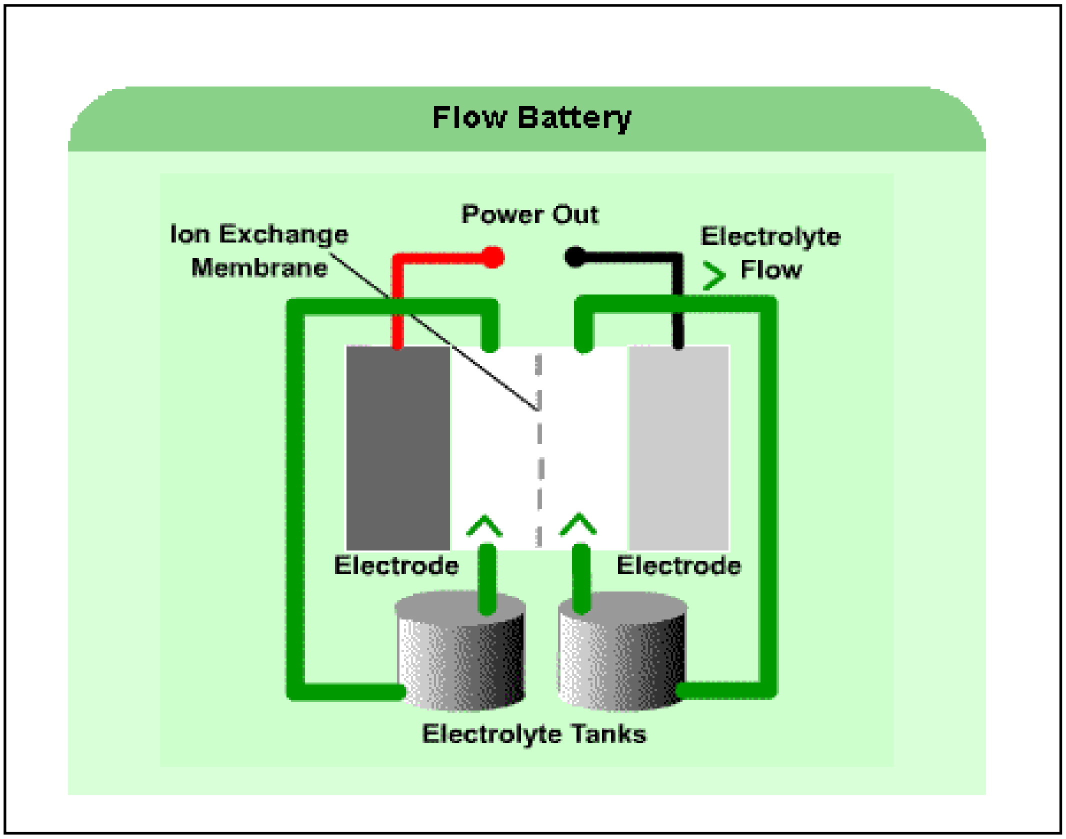


Figure B-7. Schematic of a Flow Battery.[133]

B.3.1 Basic Principles

A flow battery is a form of rechargeable battery in which electrolyte containing one or more dissolved electroactive species flows through an electrochemical cell that converts chemical energy directly to electricity. Additional electrolyte is stored externally, generally in tanks, and is usually pumped through the cell (or cells) of the reactor, although gravity feed systems are also known.[134] Flow batteries can be rapidly "recharged" by replacing the electrolyte liquid (in a similar way to refilling fuel tanks for internal combustion engines) while simultaneously recovering the spent material for re-energization.

B.3.2 Capabilities and Payoffs

As a closed system flow batteries are rechargeable and very efficient storage media. Their capacity is less than that of the pumped systems, but they have comparable efficiencies (on the order of 75-85%) and they occupy a much lower volume. The primary payoff of the system is that it can be scaled to MW energy levels.

B.3.3 Benefits to AF Base Installations

Flow batteries, and to a lesser extent hybrid flow batteries, have the advantages of flexible layout (due to separation of the power and energy components), long cycle life (because

133 Woodbank Communications Ltd, 2005.
134 Electricity Storage Association, 2009.

there are no solid-solid phase changes), and quick response times (in common with nearly all batteries). They do not require "equalization" charging and produce no harmful emissions (in common with nearly all batteries). Some types also offer easy state-of-charge determination (through voltage dependence on charge), low maintenance, and tolerance to overcharge/over-discharge.

B.3.4 Concerns, Issues, and Risks

B.3.4.1 Site Issues

Flow batteries are more complicated in comparison with standard metallic batteries as they may require pumps, sensors, control units, and secondary containment vessels. The energy densities vary considerably but are, in general, rather low compared to portable batteries, such as the Li-ion.

B.3.4.2 Cost

The main hurdle is the high cost (above $600/kilowatts/hour (kWh)) of the systems. Nevertheless, flow batteries are considered to be a viable battery technology at power scales in the high kW to low MW range, and they have been demonstrated at this scale.[135]

B.3.4.3 Technical Maturity

The technology is mature and in use in a number of locations. Vanadium redox flow batteries are currently installed at Huxley Hill wind farm (Australia), Tomari Wind Hills at Hokkaidō (Japan), as well as in other non-wind farm applications. A further 12 MWh flow battery is to be installed at the Sorne Hill wind farm (Ireland).[136] These storage systems are designed to smooth out transient fluctuations in wind energy supply. The redox flow battery cited above has a capacity of 6 MWh, which represents less than 1 hour of electrical flow from this particular wind farm (at 20% capacity factor on its 30 MW rated capacity).

B.3.4.4 Security

Since flow batteries can easily reside within the confines of an Air Force Base, security issues are minimized. Explosion risks from overloads do not affect these batteries as they do other "wet" battery systems.

B.4 Superconducting Magnetic Energy Storage

Superconducting Magnetic Energy Storage (SMES) is an emerging technology that stores energy within a magnetic field using the flow of direct current in a superconducting coil. SMES is capable of releasing megawatts of power within a fraction of a cycle to replace a sudden loss in line power. The superconducting coil must be cryogenically cooled. SMES systems are used to address power quality problems and short-term power losses, such as those that may occur while switching from grid electricity to a backup power supply. They could also be used for electricity-grid support, helping to prevent voltage collapse or voltage instability. Depending on

135 Walawalkar & Apt, 2008.
136 De Wachter, 2006.

the cost of SMES systems, this could be used to replace rechargeable battery power backup systems for individual devices.

B.4.1 Basic Principles

SMES systems store energy in the magnetic field created by the flow of direct current through a large coil of superconducting material that has been super-cooled. In low-temperature superconducting materials, electric currents encounter almost no resistance, greatly enhancing their storage capacity.

B.4.2 Benefits and Payoffs

Power is available almost instantaneously from SMES systems, and very high power output is provided for a brief period of time. There are no moving parts.

B.4.3 Concerns and Issues

The energy content of SMES systems is small and short-lived, and maintenance of the cryogenic temperatures can be a challenge. Researchers are trying to find ways to maintain the special qualities of SMES without having to keep the systems near cryogenic temperatures.[137]

B.5 Metal Based Rechargeables

B.5.1 Rechargeable Battery Characteristics

The continued strong development of Metal-Air, Lithium-Ion, Nickel-Cadmium, and Nickel-Metal Hydride (NiMH) batteries is likely to result in higher power capabilities. These technologies are being pushed by the electric vehicle industry. They are currently an expensive alternative, but as electric automobiles gain popularity such batteries may begin to infiltrate the renewable energy market. The use of the on-board battery systems on electric vehicles is commonly promoted as a means to provide the grid with a distributed storage capability. Such systems require smart power management, which will likely be incorporated into micro-grid systems of the future.

By contrast, the NaS and flow batteries discussed above are not suited to motive power due to their high operating temperatures and lower energy density (when all the controls and ancillary equipment are considered). Lead-acid batteries are the most ubiquitous metal-based secondary (rechargeable) batteries, and they are in common use as uninterruptible power supply for computer equipment in data servers and communication centers.

Development of metal-based rechargeables is expected to produce capacities of near 1 MW or better in the next five years. Currently the metal-based rechargeables are more expensive than the NaS or flow battery technologies discussed above. However, as electric automobiles gain popularity, the cost of manufacturing may drop substantially.

The following table summarizes characteristics of rechargeable batteries compiled from various open sources.[138]

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137 National Renewable Energy Laboratory, September 2009.
138 Eveready Battery Company, Inc., 2000; Electricity Storage Association, 2009; Hadhazy, 2009; and WPP Ltd., 1997.

Battery Type	Energy Density (Wh/kg)	Power Density (W/kg)	Cycle Life	Self Discharge Rate (%/month)	Charge/ discharge Efficiency	Maturity	Cost ($/kWh)
Lead-Acid	25-35	75 to 130	200-400	4	70-90%	Mature	100-125
Nickel-Metal Hydride	50-80	150-250	600-1,500	15	66%	Mature	525-540
Nickel-Cadmium	35-60	50-200	1,000-2000	20	70-90%	Mature	300-600
Lithium-Ion	100-150	300-500	400-1,200	10	80-90%	Mature	600
Lithium Polymer	130-160	100-315	400-600			Developmental	
NaNiCl	50-90	100		High		Developmental	
Zinc-Air	110-200	100	240-450		80%	Developmental	300
Vanadium Redox	25 to 50	110	400			Developmental	300

Table B-1. Rechargeable Battery Technologies.

B.5.1.1 Basic Principles

During charging, the positive active material is oxidized, producing electrons, and the negative material is reduced, consuming electrons. These electrons constitute the current flow in the external circuit. The electrolyte may serve as a simple buffer for ion flow between the electrodes, as in lithium-ion and nickel-cadmium cells, or it may be an active participant in the electrochemical reaction, as in lead-acid cells.

B.5.1.2 Benefits and Payoffs

Rechargeable batteries offer economic and environmental benefits compared to disposable batteries. While the rechargeable cells have a higher initial cost, rechargeable batteries can be recharged many times. All batteries have a finite shelf-life due to spontaneous discharge of the electrode/electrolyte system. Metal-based rechargeable battery technologies lose charge relatively quickly compared to disposable dry-cell batteries, which is why for low-power, long-duration applications like smoke detectors, dry-cell batteries are more reliable and cost-effective than rechargeables. However, for power applications relevant to the present Study, the shelf-life of metal-based rechargeables is not an issue. The more important issue is the number of deep-discharge cycles the battery can undergo. Manufacturers of NiMH rechargeable batteries claim a service life of 600-1,500 charge cycles for their batteries. Lithium-ion and related lithium-polymer batteries provide the highest energy density and lowest

mass of all the rechargeable systems currently available (Table B-1 above), and the transportation and personal electronics sectors are significant drivers for the technology.

B.5.1.3 Concerns and Issues

Lead-acid is one of the oldest and most developed battery technologies. While the energy density is relatively low, their power density, and their ability to handle high surge currents make them a viable high power storage option. Although ubiquitous, lead-acid batteries suffer from a relatively small number of recharge cycles (especially when undergoing repeated deep-discharges), a low energy density, and environmental concerns regarding the toxicity of lead. Similar limitations exist for nickel-cadmium batteries. Although they are currently used in peak-shaving applications, the above concerns limit their potential use in future power systems.

The main limitation of Li-ion, NiMH, and Li-polymer technologies is the high cost (greater than $600 per kilowatt-hour (kWh)) due to special packaging and the need for internal overcharge protection circuits. While Li-ion has been successfully employed at the power transmission level to stabilize very short-duration phase fluctuations, they have not yet been demonstrated to be cost-effective for longer duration power (minutes to days).[139]

B.5.2 Metal-Air Batteries

In Metal-Air batteries, the anode is a pure metal and the cathode uses an inexhaustible supply of air. This means that the possibility of having a large energy density is only design-limited. The power density however is low, so a metal-air battery can only supply low currents over a long period of time. Metal-air batteries are the most compact and, potentially, the least expensive batteries available, these features alone make them attractive. The most prevalent metal-air battery is the ubiquitous zinc-air cell, used in hearing aids and other low-power applications.

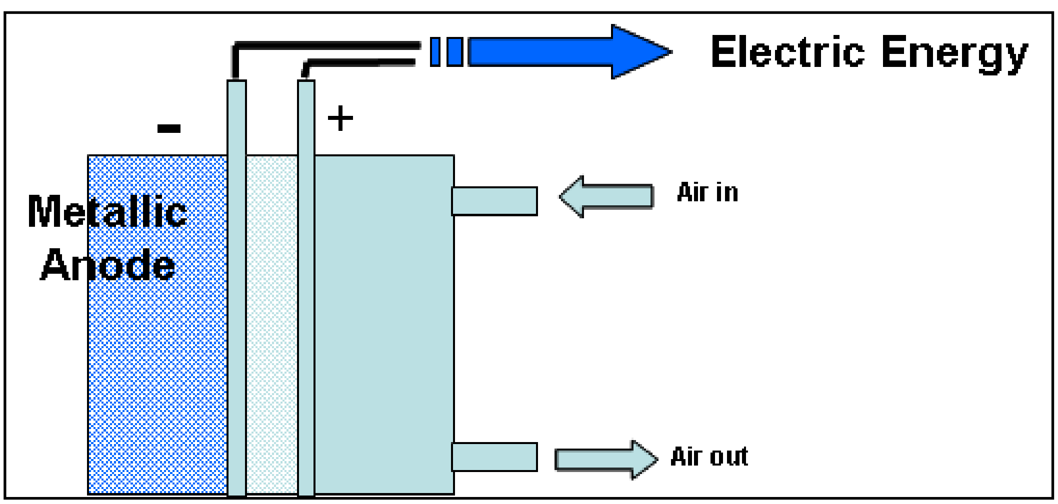

Figure B-8. Schematic of a Metal-Air Battery.

139 United States Electricity Advisory Committee, 2008.

B.5.2.1 Basic Principles

Metal-air batteries have a lot of in common with fuel cells in which the anode is an active metal and air is the potentially unlimited cathode. These batteries have low power and the lowest power efficiency of any of the battery systems (40-50%), but high energy densities are theoretically possible and have been demonstrated in several metallic systems.

B.5.2.2 Benefits to Air Force Base Installations

Metal-air batteries have very little to offer Air Force Bases as system or grid back-ups. Their primary uses would be powering low power systems for long times at low cost. They are among the lowest cost per kWh systems available. They are not applicable to grid size power and energy systems.

B.5.2.3 Concerns, Issues, and Risks

- **Site Issues:** These batteries are not applicable to restoring power to a grid-based network or node. They could provide low power over long times for small appliances and computer peripherals. They are limited by problems such as dry-out, limited power, limited temperature operation, and corrosion.
- **Cost:** These are the lowest cost batteries on the market today in terms of energy density per dollar, but they are among the poorest in power per dollar. They are the battery of choice when the need is low-level, compact power generation over a very long period of time.
- Technical Maturity: This technology is mature and is in use in many different devices that use low power output—such as hearing aids and other low power applications. Energy densities (as noted before) are among the highest.
- Security Irrelevant to the current discussion.

B.5.3 Lithium Ion Battery

The cathode in Lithium-Ion batteries is a lithiated metal oxide (such as $LiCoO_2$) and the anode is made of layered, graphitic carbon. The technology is well-infiltrated in the rechargeable device market (e.g., cell phones, laptop computers). The systems provide a higher energy density than Nickel-Cadmium batteries and they generally survive more charge/discharge cycles. Another major attraction of this technology is the lower toxicity and environmental hazard of the elemental components relative to cadmium or lead-based batteries.

B.5.4 Nickel Cadmium Battery

Nickel-cadmium batteries are a type of rechargeable battery that uses nickel oxide hydroxide and metallic cadmium electrodes. Cost and lower energy density limit their use in stationary power.

B.5.5 Utility-Scale Storage Batteries

Location	Year	Capacity	Technology	Purpose
Fairbanks, AK	2003	40 MW for 7 minutes or 27 MW for 15 minutes	Nickel-cadmium batteries	Stabilize voltage and reduce power blackouts
Huxley Hill Wind Farm, Tasmania, Australia	2003	200 kW for 4 hours	Vanadium redox flow battery	Load balancing
Sorne Hill Wind Farm, Donegal, Ireland	TBD	2 MW for 6 hours	Vanadium redox flow battery	Load balancing
Futamata Wind Farm, Japan	2008?	34 MW for 4 (?) hours	Sodium-sulfur battery	Load balancing
Chemical Station in Charleston, WV	2006	1.2 MW for 4 hours	Sodium-sulfur battery	Peak shaving
Milton, WV	2008	2 MW for 4 hours	Sodium-sulfur battery	Peak shaving, backup power
11.5 MW Minwind Energy wind farm	2008	1 MW for 7 (?) hours	Sodium-sulfur battery	Load balancing (reduce cycling of power plants)

Table B-2. Deployed and Planned Utility-Scale Storage Battery Systems.

This section summarizes some examples of the battery technologies described in the previous four sections to as applied to utility-scale power systems of relevance to Air Force Bases. Large utility-scale (1 to 10s of MW) electric storage using batteries have been demonstrated and are available today, although cost is still the main obstacle to the widespread adoption of the technology. This is expected to change as more and more very large scale (10 to 100 MW) intermittent renewable energy systems are built and connected to the grid, which necessitates deployment of large scale electric storage capabilities for smoothing of transient fluctuations, load balancing and peak shaving. Examples of deployed and planned systems are listed above in Table B-2.

B.6 Pumped Storage

A viable, low-cost energy storage solution for some bases may be compressed air or pumped hydro. These options depend heavily on the geography of the base. These low-cost options for energy storage are being promoted in regions where there is a well-defined basin at elevation (for water) or an impermeable-wall underground cavern (for air) available locally.

Today there are several forms of pumped energy storage: hydro, compressed air, and advanced compressed air systems. All of these systems convert electrical energy into potential energy, but they store the energy in different forms of potential energy.

B.6.1 Pumped Hydroelectric Storage

The first application of large-scale energy storage (31 MW) in the United States began in 1929, when the first pumped hydroelectric power plant was placed into service.[140] In a pumped storage system water is pumped from a lower elevation reservoir during times of low demand to a higher elevation reservoir. When required, the water flow is reversed to generate electricity. Where geography permits, this is a very sound option.

Hydroelectric storage is used by several regional energy suppliers to provide peak leveling for their larger power plants and to share energy with other members of the power grid during times of heavy demand. The first application of large-scale energy storage (31 MW) in the United States occurred in 1929, when the first pumped hydroelectric power plant was placed into service at Connecticut Light & Power's Rocky River Station.[141] In a pumped storage system, water is pumped from a lower elevation reservoir during times of low demand to a higher elevation reservoir. When required, the water flow is reversed to generate electricity.

B.6.1.1 Basic Principles

Pumped hydroelectric storage uses electric powered pumps to pump water from a lower reservoir into an elevated reservoir, generally in a natural or dammed depression in the geography of an area. When electricity is needed, the water is allowed to flow back to the lower reservoir through water-driven electric turbines.

B.6.1.2 Capabilities and Payoffs

The primary payoff of the system is that it can develop gigawatt (GW) levels of energy over relatively long periods of time, depending on the size of the reservoirs and the difference in elevation. Energy can be stored during periods of excess available energy, such as late night-early morning, and it can be recovered during high demand. While the efficiency of energy conversion is poor (on the order of 40-50%), it is more than made up from the change in energy rates between peak and off-peak times.

140 Electric Storage Association, 2009.
141 United States Electricity Advisory Committee, 2008.

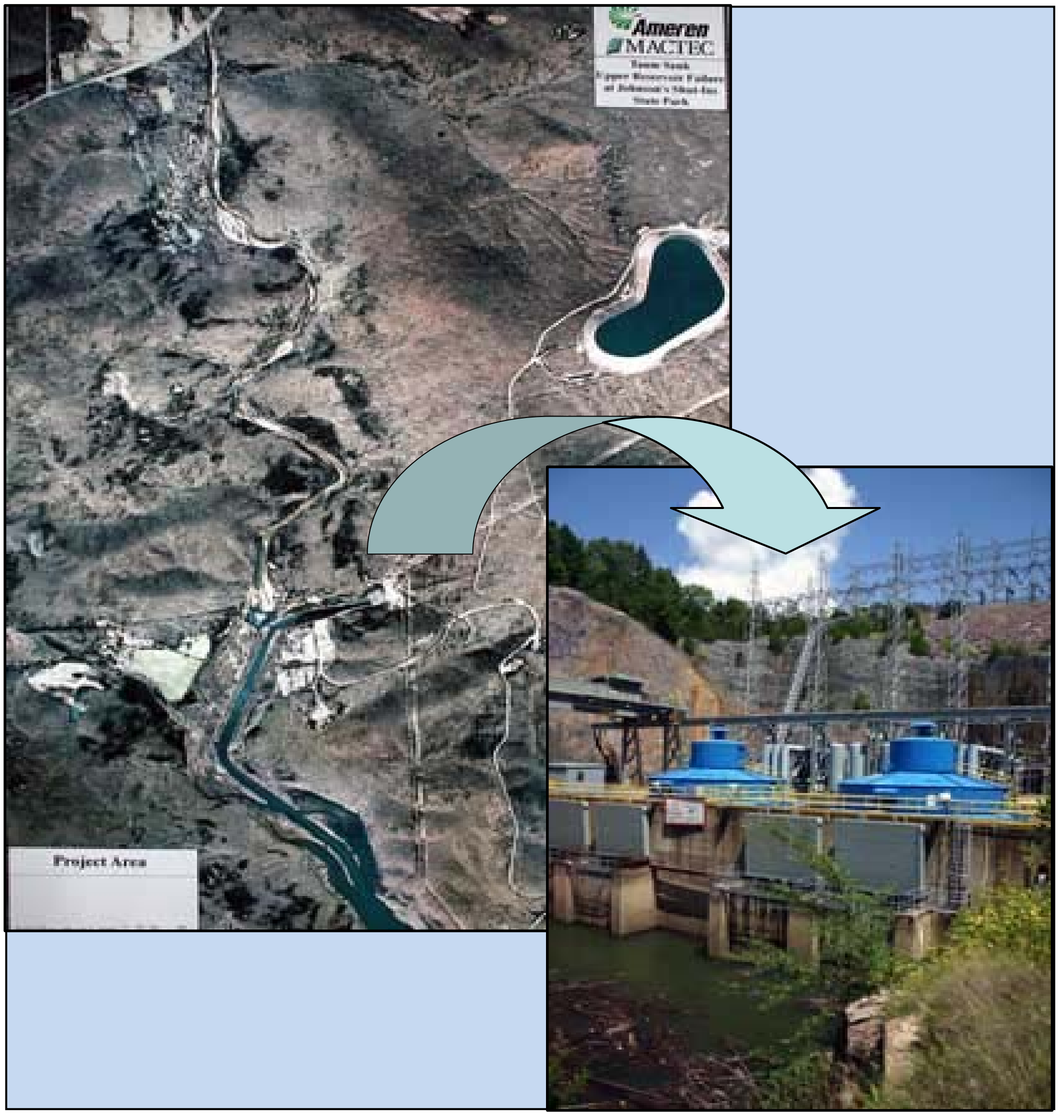

Figure B-9. Taum Sauk Mountain Pumped Hydroelectric Storage System.[142]

B.6.1.3 Benefits to Air Force Base Installations

Benefits to Air Force Bases were determined to be small because the area required to store sufficient energy to power a 40-50 MWh system for up to two weeks is very large and few bases have either the geography or the change in elevation required to include this as an energy storage option.

B.6.1.4 Concerns, Issues, and Risks

- **Site Issues:** The base must be large enough to hold a reservoir of the size needed to power the energy needs of the site. It must have the elevation difference required to provide the energy needed to drive a turbine and create the power needed to generate the electric energy required.

142 Spradley, 2006.

- **Cost:** The costs are similar to those encountered in a conventional hydroelectric plant: pumps and turbines, construction of the dam(s) and land costs.
- **Technical Maturity:** The technology is mature and in use in several installations around the country as peak reductions for large municipalities.[143]
- **Security:** There are security issues surrounding these forms of energy storage. There is a risk of a dam rupture, which happened at the Taum Sauk reservoir in Missouri in 2007 (Figure B-9). When the dam failed due to a lack of maintenance, the energy released in a 500 foot fall of 1.3 billion gallons of water[144] redefined some major recreational park lands in the state. The immediate loss of energy was not reported.

B.6.2 Compressed Air Energy Storage (CAES)

Currently receiving significant attention for use in large-scale energy storage is compressed air energy storage. In this technology, air is pre-compressed and stored in caverns, salt domes or depleted gas fields. The pressurized gas could be used to drive a simple turbine-based electric generator directly, although the energy content is not sufficient to make this cost-effective. Typically, the compressed air is used in conjunction with a natural gas-fired turbine, which then drives an electric generator. Like a supercharger, the use of compressed air increases the energy output and overall efficiency of the system. It should be pointed out that such a system requires the use of fossil fuel, and so the designation of this technology as "renewable" is subject to legislative interpretation.

B.6.2.1 Conventional Compressed Air Energy Storage

Compressed air energy storage can take two forms. The more traditional approach uses the compressed air to drive a turbine to supercharge a natural gas-burning generator in order to increase the efficiency of the generator in producing electric power. The advanced approach uses the same device to both compress the air in a cavern and to recover the power coming out of the compressed air as it turns a turbine. These will be addressed separately, and the first of these in this section.

B.6.2.1.1 Basic Principles

In conventional compressed air energy storage, air is pre-compressed and stored in caverns, and other formations, such as salt domes and depleted gas fields (see Figure B-10 below). When needed the air is combined along with some gas fuel to spin a turbine to generate electricity.

B.6.2.1.2 Capabilities and Payoffs

The primary payoff of the system is that it develops MW energy levels from air compressed over short periods of time and stored in natural (or man enhanced/sealed) caverns. The compressed air is used to enhance the performance of a conventional combustion turbine driven generator. Thus moderate energy demands can be met by using excess energy from the grid over long periods of time to provide this compressed air. Payoffs during high demand times

143 See, for example: Riverbank Power Corporation, 2009.
144 Spradley, 2006.

are met using energy gained during low cost periods. The technology has been well demonstrated at levels greater than 100 MW.[145]

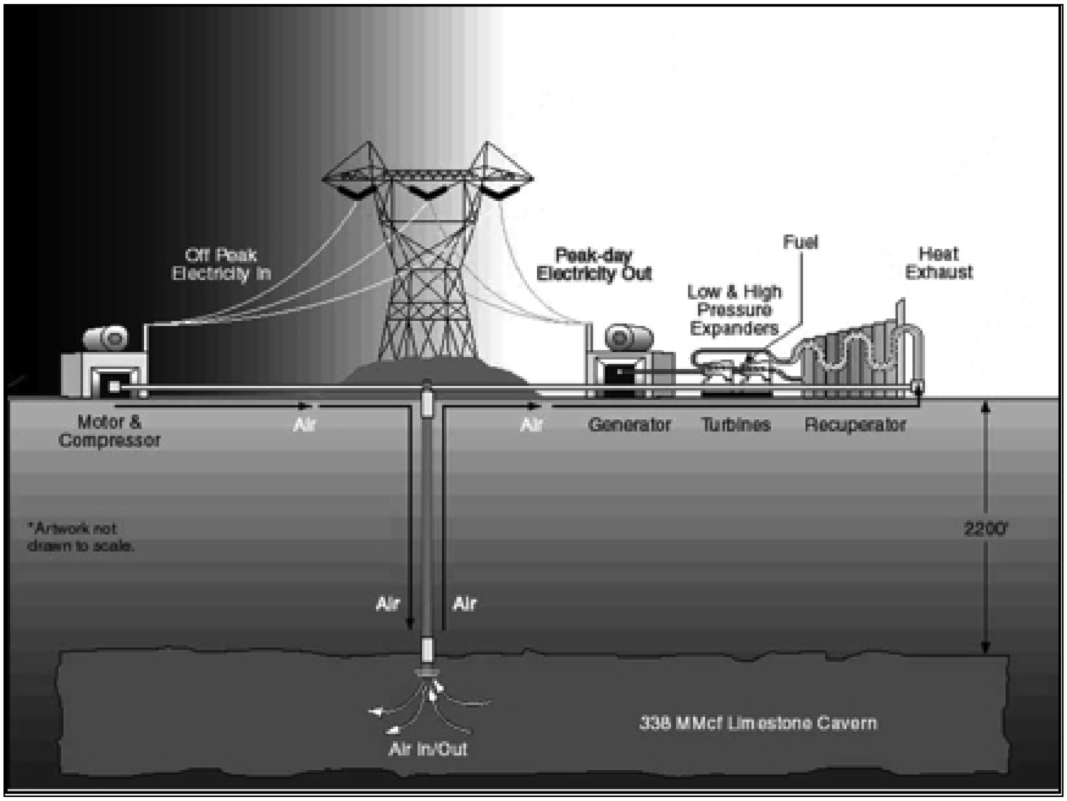

Figure B-10. Schematic of a Conventional Compressed Air Energy Storage System.

B.6.2.1.3 Benefits to Air Force Base Installations

Benefits to Air Force Bases could be large where natural caverns exist and would not require unusual effort to seal. However, the number of bases for which this alternative would be found valuable is thought to be small. The volume required to store sufficient energy to power a 40-50 MWh system for up to two weeks is quite large.

B.6.2.1.4 Concerns, Issues, and Risks

- **Site Issues:** The base must have a cavern large enough to hold sufficient compressed air to power a generator capable of providing the energy needs of the site. Even for those sites having such caverns, unless they are naturally sealed, the cost of sealing the cavern can be prohibitive.
- **Cost:** Generally the cost of the pumps and turbines are much lower than those used for hydroelectric options since the air-based systems are much smaller. The cost of sealing the cavern, if necessary, is the driver for the system. CAES technology also requires conventional hydrocarbon fuel in the discharge cycle, which introduces an

145 United States Electric Advisory Committee, 2008.

operational cost (for the fuel), which is expected to be much larger than typical operations and maintenance costs of renewables such as solar or wind.

- **Technical Maturity:** The technology is mature and in use in several installations around the country to provide peak power for large municipalities.
- **Security:** Since compressed air systems would reside within the confines of an Air Base, security issues are not significant. Should the cavern extend beyond the confines of the base, then there would be some risk of loss of pressure were the system breached. This risk could be minimized by configuring the generator to allow for running in a non-turbocharged condition (at a lower efficiency) if necessary.

B.6.2.2 Advanced Compressed Air Energy Storage

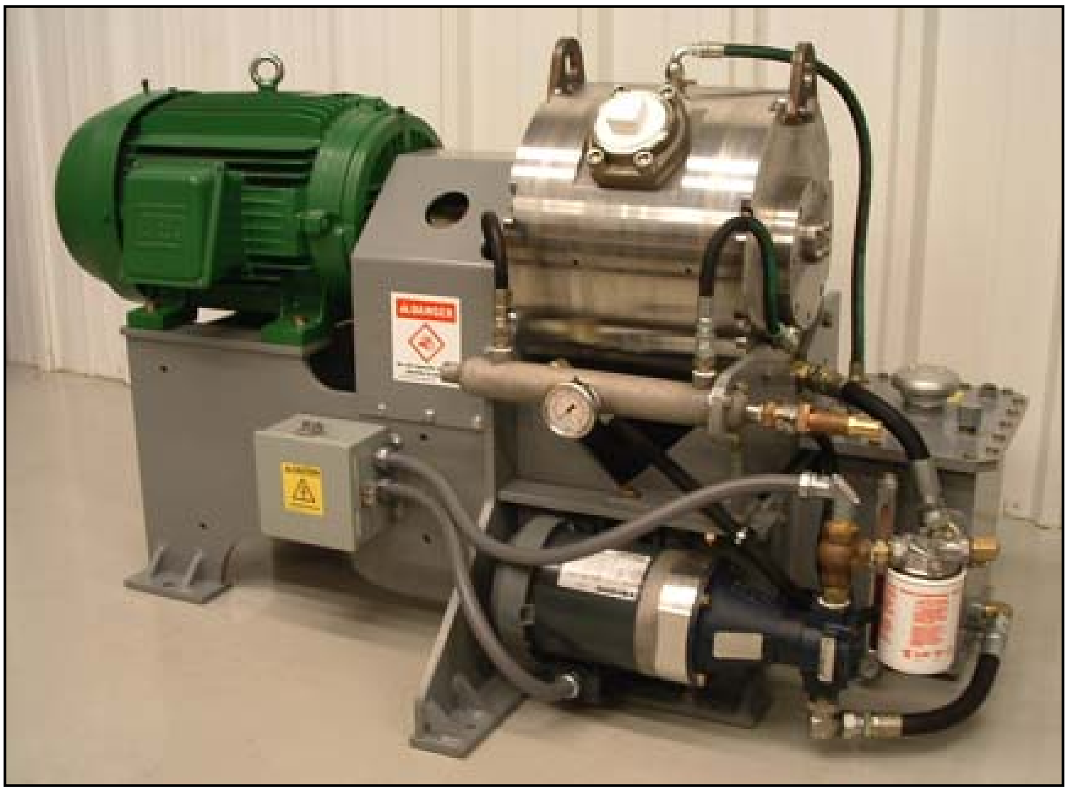

Figure B-11. Star-Rotor 25 KW In-Line Compressor/Pump - Generator System.

The advanced approach to compressed air energy storage uses the same device to both compress the air in a cavern and to recover the power coming out of the compressed air as it turns a turbine. A very efficient compressor must be used to drive the system. In this case the compressed air alone can be used to drive the turbine and the power generation system—that is, no hydrocarbon combustion is needed. The data presented herein comes from StarRotor, Inc.[146]

146 Murphey, Rabroker & Holtzapple, 2009.

B.6.2.2.1 Basic Principles

In advanced compressed air energy storage, air is pre-compressed and stored in caverns, and other formations, such as salt domes and depleted gas fields. When needed the air is released to drive the compressor in reverse and thus to drive the generator to produce electricity.

B.6.2.2.2 Capabilities and Payoffs

With motor, compressor/turbine, and generator all as axial devices on the same shaft, the system can be very efficient (on the order of 75-85%). The primary payoff of the system is that it develops kW energy levels by compressing air over short periods of time by storing the compressed air in natural (or man enhanced/sealed) caverns, then using this compressed air to drive a turbine-driven generator. For a given power plant/air reservoir size, the total energy output of such systems is lower than for CAES.

B.6.2.2.3 Benefits to AF Base Installations

As with conventional compressed air systems, large natural caverns must exist and they must not require unusual effort to seal. Few bases have accessible caverns the size required to make it a viable energy storage medium.

B.6.2.2.4 Concerns, Issues, and Risks

- **Site Issues:** The base must have a cavern large enough to hold sufficient compressed air to power a generator capable of providing the energy needs of the site. Even for those sites having such caverns, unless they are naturally sealed, the cost of sealing the cavern can be prohibitive.
- **Cost:** The cost for sealing the cavern, if necessary, is the driver for the system. Energy losses due to pressure leaks will also factor into costs.
- **Technical Maturity:** The technology is not yet mature for the axial advanced systems, and their power rating is only 25 kW for the largest of the systems demonstrated today. It is not clear when or if systems with MW capability will become available.
- **Security:** Since compressed air systems can easily reside within the confines of an air base, security issues are minimized. Should the cavern extend beyond the confines of the base, then there would be some risk of loss of pressure were the system to be breached. A significant breach would disable the power generation system.

B.7 Fuel Cells

Fuel cells should be considered a primary source of electric power, rather than an electricity storage medium. This is particularly true for hydrocarbon based fuel cells to be described in more detail below. However, if hydrogen is used as the fuel source, a fuel cell can be considered a secondary storage medium as well. In this case, hydrogen is directly produced from electricity through the electrolysis of water, the hydrogen is stored in an appropriate receiver, and the hydrogen is converted back to electricity when needed.

B.7.1 Basic Principles

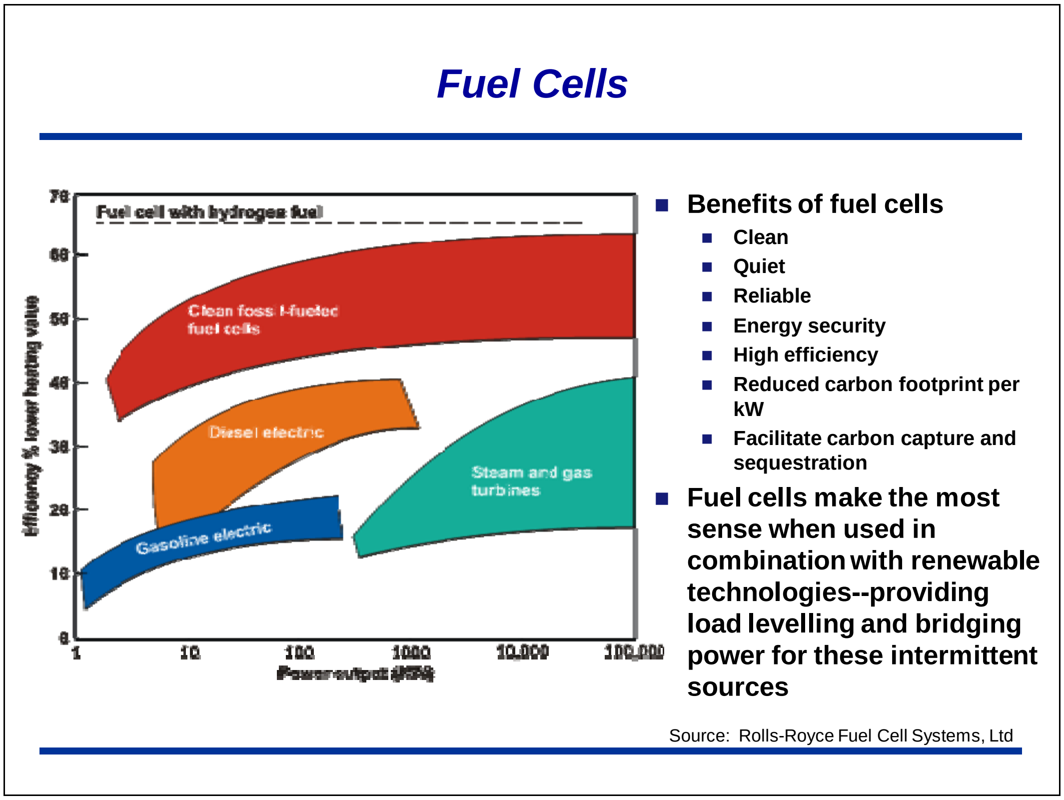

Figure B-12. Some of the Benefits of Fuel Cells. (The plot compares general efficiency ranges as a function of size for five different methods to convert fuels to electricity. An internal combustion engine driving a rotary electric generator converts ~15% of the energy in gasoline to electricity. The corresponding efficiency of a large diesel engine can be ~38%. Large coal power plants using steam are ~ 35%, and natural gas plants using combined cycle technology can be ~45%. High temperature fuel cells, when combined with heat recovery turbines are predicted to be close to 60%. The limit for a hydrogen fuel cell is ~65%. The lower heating value used in the calculation assumes that the heat content of water vapor is not recovered. Notional plot courtesy of Rolls-Royce Fuel Cell Systems, Ltd.)

A fuel cell is a device that oxidizes a fuel to produce electrical power directly, without combustion (Figure B-12 above). A fuel cell behaves is similar to a primary battery, deriving electric current from the controlled oxidation of a fuel and the controlled reduction of an oxidant (usually oxygen). Unlike a battery, which derives its energy from a reactive metal such as lead, lithium, or zinc, a fuel cell derives its energy from a gaseous fuel such as hydrogen or methane. Some fuel cells can use more complex fuel feedstocks such as sugars or liquid hydrocarbons.

Fuel cells are significantly more efficient than equivalent internal combustion engines because they convert chemical energy to electrical current directly, rather than via the mechanical conversion of heat energy. Their modular nature allows fuel cells to be stacked in parallel or in series combinations to match the specific output power requirements.

Molten Carbonate Stationary Fuel Cell
Barksdale AFB, LA

Goal: Install reliable, grid-independent, environmentally "clean" Molten Carbonate Fuel Cell technology by demonstrating a 300kW – 2MW system at Barksdale AFB. Configure compatible fuel cell stack designs for modularity and expansion. Conduct future expansion that will include thermal recovery of heat for use within base facilities and possible production of hydrogen.

Milestones

- Introduce Molten Carbonate Fuel Cell technology to AF/Barksdale AFB
- Initial production of 300kW grid power, expand system to 1-2MW
- Recover heat to be used in facilities
- Potential plan for future configuration to support H_2 vehicles and aircraft support equipment

Figure B-13. FuelCell Energy, Inc. is Installing a 300 kW Fuel Cell Designed to Run on Natural Gas at Barksdale Air Force Base in Louisiana. (The vendor anticipates the system will be online in early 2010. The power plant was acquired to improve the availability of reliable and environmentally friendly electricity for the base.[147]*)*

The simple nature of their design (no moving parts or excessive temperatures) makes fuel cells highly reliable. If pure hydrogen is used as a fuel then the only outputs are electricity, water vapor, and a small amount of heat; if a hydrocarbon fuel is used then carbon dioxide is also generated. In this way fuel cells are seen as being significantly more environmentally friendly than other hydrocarbon-fueled power sources.

At present most systems are limited by the amount of current they can generate and longevity of the electrodes. Systems have been demonstrated with conversion efficiencies as high as 60%; by contrast, the efficiency of burning the hydrocarbon in a turbine system to generate electricity is closer to 40%. This improved efficiency, along with a significant reduction in nitrogen oxides and other polluting by-products of combustion provides a driver for development of the technology. Substantial research and development of fuel cell systems is underway, nationally and internationally.

There are a number different fuel cell types: polymer exchange membrane fuel cell, solid oxide fuel cell, alkaline fuel cell, molten carbonate fuel cell (Figure B-13 above), phosphoric acid fuel cell, and direct methanol fuel cell. For stationary power applications, solid oxide and molten carbonate fuel cells are the most utilized. These fuel cells operate at high temperatures

147 Fuel Cell Energy, Inc., 2009.

(between 600 and 1,000 degrees C). This high temperature makes reliability a problem, because components of the fuel cell can break down after cycling on and off repeatedly. Molten carbonate fuel cells operate at lower temperatures (~600 degrees C) However, when in continuous use, solid oxide fuel cells have been found to be the most stable fuel cell type. The high temperature also has an advantage: the steam produced by the fuel cell can be channeled into turbines to generate more electricity. This process is called co-generation of heat and power and it improves the overall efficiency of the system.

B.7.2 Benefits and Payoffs

As a power source, fuel cells are very useful as power sources in remote locations, such as spacecraft, remote weather stations, large National or State Parks, rural locations, and in certain military applications. A fuel cell system running on hydrogen can be compact and lightweight, and have no major moving parts. Because fuel cells have no moving parts and do not involve combustion, in ideal conditions they can achieve high reliability.

B.7.3 Concerns and Issues

As an energy storage device a fuel cell is a poorer device than its cousin, the flow battery. Fuel cells cannot be recharged like a secondary battery, but in some applications, such as stand-alone power plants based on discontinuous sources such as solar or wind power, they are combined with electrolyzers and storage systems to form an energy storage system. The overall efficiency (electricity to hydrogen and back to electricity) of such plants (known as *round-trip efficiency*) is between 30 and 50%, depending on the system. While a much cheaper lead-acid battery might return about 90%, the electrolyzer/fuel cell system is more scalable to large energy applications.

B.8 Other Storage Systems

Several other energy storage options are potentially applicable to short-term grid energy support, though they are not well-proven. Of these, flywheels and electrochemical capacitors were reviewed by the Panel. Although an exception may be made for flywheels,[148] these systems are all geared toward more rapid discharge of energy, and are not particularly suited to the longer term energy storage needs of renewable energy systems articulated in this Report.

B.8.1 Flywheels

B.8.1.1 Basic Principles

Flywheels are energy storage devices that consist of a massive rotating cylinder that is substantially supported on a stator by magnetically levitated or very low friction bearings that eliminate bearing wear and increase system life. A flywheel can be combined with a device that operates either as an electric motor that accelerates the flywheel to store energy or as a generator that produces electricity from the energy stored in the flywheel. The faster the flywheel spins the more energy it retains. Energy can be drawn off as needed, slowing the flywheel.

Modern flywheels use composite rotors made with carbon-fiber materials. The rotors have a very high strength-to-density ratio, and rotate in a vacuum chamber to minimize

148 Walawalkar & Apt, 2008.

aerodynamic losses. The use of superconducting electromagnetic bearings can virtually eliminate energy losses through friction.

B.8.1.2 Benefits and Payoffs

Flywheels can discharge their power either slowly or quickly, allowing them to serve as backup power systems for low-power applications or as short-term power quality support for high-power applications. They are little affected by temperature fluctuations, take up relatively little space, have lower maintenance requirements than batteries, and are very durable.

B.8.1.3 Concerns and Issues

Doubling the rotational speed of a disk or flywheel quadruples the stored energy, so increasing rpm significantly increases the energy density of a flywheel. Operating at higher revolutions per minute necessitates fundamental differences in design approach. While low-speed flywheels are usually made from steel, high-speed flywheels are typically made from carbon or carbon and fiberglass composite materials that will withstand the higher stresses associated with higher rpm. Higher rpm also creates greater concern with frictional losses from bearings and air drag. High-speed flywheels universally employ magnetic bearings and vacuum enclosures to reduce or eliminate these two sources of friction. Magnetic bearings allow the flywheel to levitate, essentially eliminating frictional losses associated with conventional bearings.

B.8.2 Electrochemical Capacitors

Electrochemical capacitors store electrical energy in the form of electrons loaded on a conducting plate. It is in a sense a hybrid between a capacitor, in which energy is stored in the form of electrons on a metallic plate, and a battery, in which energy is stored in the form of chemical bonds. Because no chemical reaction is involved in charging a capacitor, the efficiency and recyclability of such systems is quite high. The speed of discharge is also quite large. The energy density of a capacitor is typically a factor of 10 lower than is found in a battery. In Electrochemical Capacitors, the distance in which electron storage occurs is a few angstroms, and the capacitance and energy density of these devices is larger than electrolytic capacitors.

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Appendix C: Expeditionary Energy Technologies

As a general rule, expeditionary and forward operating bases are not energy efficient due to their operational requirements of high mobility and high security. The high cost and associated risks of transporting fuel in the field have become painfully obvious in recent years. Even small improvements in efficiency or energy conservation in an expeditionary base provide large gains in reducing the risk of exposure of fuel convoys to roadside bombs and other disruptions, and the calculations that might make renewable energy sources uneconomical in the continental United States or more secure environment are much different here. Waste management and water systems are also key components of the energy consumption picture that need to be treated differently in expeditionary operations. The Panel identified a number of available energy production and storage systems of relevance.

Expeditionary Bases

- Expeditionary base systems not energy-efficient
  - Uses inefficient diesel powered electric generators
  - Focus is on transportability, not energy efficiency
  - Does not include waste management system
  - Significant opportunities exist in energy conservation and generation
- Technologies for local energy conservation:
  - Energy conservation technologies
  - Technologies for increasing energy efficiency
- Technologies for local energy generation:
  - Large scale (100 KW to 1MW class) deployable renewable systems
  - Multi-fuel electric generators
  - Lightweight, highly efficient power generation systems
  - Large-scale waste-to-energy conversion systems

Figure C-1. Some Alternative Power Systems Relevant for Expeditionary Bases.

C.1 Waste to Energy

Waste-to-energy or energy-from-waste, the process of creating energy in the form of electricity or heat from the incineration of a waste source, was discussed in detail in Appendix A (Section A.16), and the plasma incineration system being installed at Hurlburt Field was highlighted. Such a system could be designed for deployment, although the amount of waste generated in an expeditionary setting would be too small to provide a net production of energy

with the current technologies. However, the reduction in the amount of waste that must be transported and disposed of provides an incentive for some expeditionary scenarios, even if the system is run at break-even or at a slight deficit in energy. A transportable incineration system could also alleviate other security issues associated with Forward Operating Bases (FOBs), including the elimination of open burning in deployed locations and the minimization of plumes that can be observed by hostile forces. The Air Force Research Laboratory Airbase Technologies Division (AFRL/RXQ) has developed a prototype transportable waste-to-energy system.[149]

C.2 Large Scale Deployable (Portable) Renewable Systems

There is a critical need for large scale (100 kilowatt (kW) to 1 megawatt (MW) class) deployable solar and wind renewable systems to augment standard BEAR (Basic Expeditionary Airfield Resources) bases. An 1,100-man BEAR base power system consists of 5 MEP-12 (750-kW) diesel electric generators (4 running, 1 spare). Each MEP-12 weighs 25,374 pounds and requires one C-130 aircraft for airlift. One MEP-12 consumes approximately 55 gallons (gal) of JP-8 or diesel fuel per hour, resulting in a per-day fuel consumption for an 1,100-man deployment of 5,280 gallons of fuel generating an average of 3 MW. At $3.00/gal, this equates to $15,840/day, not including transportation costs. The fully burdened cost of the fuel delivered to the FOB can be much larger; In 2005, the Air Force Financial Management and Comptroller office estimated the cost of transporting and protecting the fuel delivered in-air added $24.38/gal to the fuel cost; and the Army 3-stage re-supply battlefield scenario (delivery to FOB on-ground) adds about $400 to the cost of a gallon of fuel.[150] Thus the total cost of fuel used to generate electric power can be as much as $2 million (M) per day for a 1,100-man deployment.

Scaling the Nellis Air Force Base 14.2 MW solar photovoltaic system down to a 1 MW (peak) system based on current technologies would cost on the order of $10M, not including additional costs associated with overseas installation, and it would require approximately 10 acres of land. This system, if deployed to augment a standard BEAR base in a region with a solar resource similar to the Las Vegas, Nevada area, would offset 0.3 MW of generation capacity, for a savings of about 500 gallons of diesel fuel per day. Using the fully burdened cost of fuel delivered to an FOB on-ground from the numbers above, the dollar savings is $200,000/day, or a complete payoff of the $10M investment (overnight costs) in 50 days. Deployable solar thermal and wind turbine systems are also expected to yield near-term cost savings, although scalability and deployment costs could vary substantially. The in-field operations and maintenance costs and security issues are not considered in the above analysis.

Since deployability considerations (lighter weight, modularity for rapid assembly, etc.) are not likely to be considered in current commercial system development, a focused research and development (R&D) effort by the AF would be prudent. Potential R&D topics include:

- Assessment of current technologies for deployed systems,
- Multi-fuel capability for generator systems,
- Lightweight solar photovoltaic systems,
- Modular solar thermal systems; and

149 AFRL Materials & Manufacturing Directorate, n.d.
150 White-Olsen, 2005.

- Wind turbine systems optimized for deployment.

In addition, efficient fuel cell systems that utilize liquid hydrocarbon fuels are of particular interest. This topic is discussed in more detail earlier in this report, and below.

C.3 Technologies for Increasing Efficiency

Gains in energy efficiency from use of new technologies should be augmented by energy conservation strategies, using both commercial off-the-shelf components and focused R&D into new energy conservation technologies. There are presently several facilities across Air Force installations using solar water heating and solar generation of thermal energy. Existing technologies for solar water heating include flat-plate and evacuated-tube collectors, but new developments include the introduction of low-cost polymer collectors and freeze-proof piping. A solar ventilation air preheating system is a well-established energy saver for colder climates that should be implemented where appropriate. Super insulators, such as phase change materials, show promise as thin, lightweight components with high insulation value for shelter skins. Probably one of the more revolutionary developments to watch is light emitting diode (LED) lighting. Although compact fluorescent lights are a great energy-saving step for fixed installations, they are constructed of breakable glass tubes that contain small amounts of toxic mercury. The advantages and challenges (primarily cost) of LED systems were discussed earlier in this report. The more compact, more efficient, longer-lived, and rugged nature of LED lighting presents significant advantages for portable and expeditionary environments. LED flashlights, in particular, provide an advantage in reducing the amount of batteries that need to be brought into the field.

C.4 Lightweight, Highly Efficient Power Generation Systems

C.4.1 Lightweight, Highly Efficient Power Generation Systems

For foreseeable future, diesel-powered electric generators will continue to be the primary source of power generation for expeditionary forces. There is a unique Department of Defense need for light-weight, highly efficient power generation systems using diesel fuel. Potential research topics include:

- Light weight engines,
- Higher efficiency multi-stage systems, and
- Co-generation system concepts.

AFRL/RXQ’s Deployed Base Systems Branch (AFRL/RXQD) is developing a multi-fuel electric generator to provide airbase energy needs. The developed system is planned to be 40% more efficient than current electric power generation units with a 50% reduction in footprint. Current power generation systems are inefficient, noisy, bulky, and limited to diesel fuel. The vision for the technology is that it can be run on a variety of liquid fuels including bio-fuels, and it can be applied to a multitude of applications from battery charging to large 750 kW electric generation units.

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Appendix D: Microgrid Technologies

Relevant to Recommendation 2

A micro-grid is defined as an aggregation of electrical loads and generation that contains a local Energy Management System (EMS). The generators in the micro-grid may be micro-turbines, fuel cells, reciprocating engines, or any of a number of alternate power sources. A micro-grid may serve a shopping center, industrial park, college campus or an Air Force Base (AFB). From the perspective of the power utility, a micro-grid is an electrical load whose magnitude can be controlled by the EMS. The load could be constant, or the load could increase at night when electricity is cheaper, or the load could be held at zero during times of system stress (Figure D-1 below).

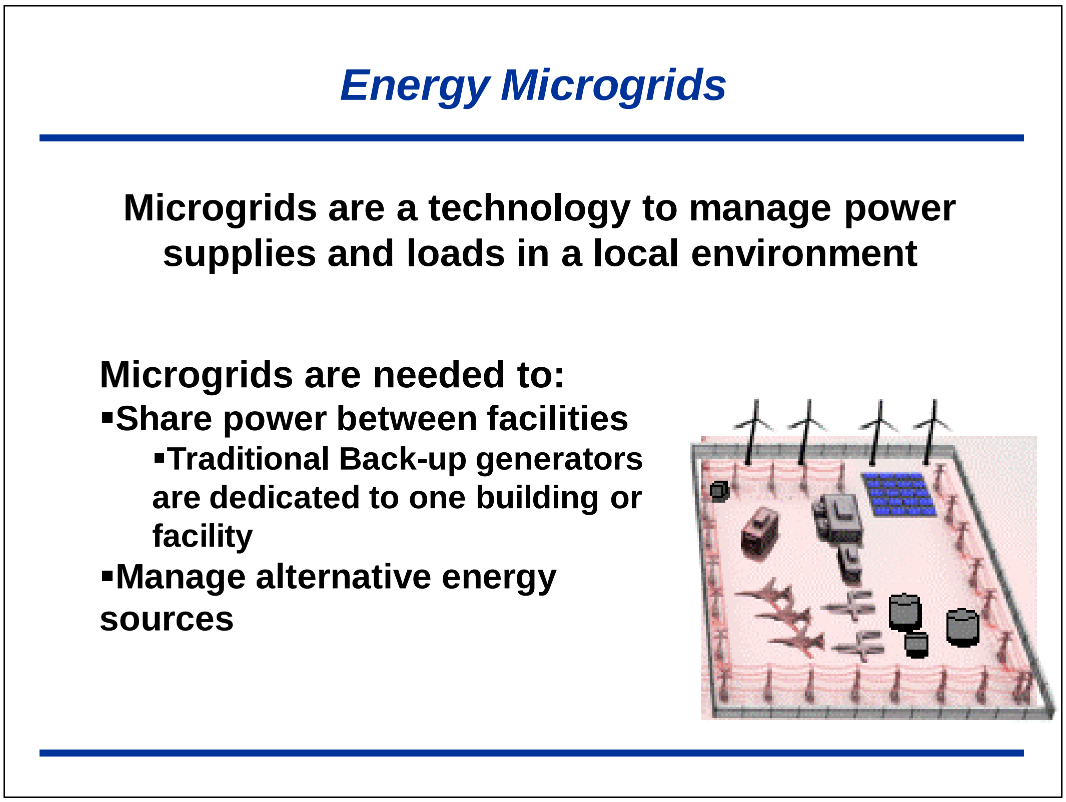


Figure D-1. Microgrids Are Key to Balancing Energy Generation and Loads On an Installation Such as an Air Force Base.

The microgrid can utilize waste heat from generators to improve overall efficiency. The EMS is used to make decisions regarding the best use of the generators for producing electric power and heat. These decisions will be based upon the heat requirements of the local

equipment, weather, price of electric power, cost of fuel and other considerations. The EMS will dispatch the generators and provide an overview of the Combined Heat and Power system.[151]

D.1 Basic Principles

The micro-grid will supplement the existing grid structure by adding high-reliability generation near critical loads, by adding storage at critical locations and by introducing sustainable generation on a local scale. Storage in the micro-grid is essential to stabilize the operation of the system. Fuel storage allows for the generation of electricity without dependence upon the grid. Electricity storage provides fast response to the changing needs of the micro-grid. It also raises the level of security and reliability of the Energy Surety Micro-grid's (ESM) generators. Thermal storage can be included, if waste heat is to be recovered from on-site generators and subsequently applied to loads as well as for the implementation of Solar Hot Water Heating and Concentrating Solar Power systems as electricity generation supplies. Fuel, electrical, and thermal storage near the load balances the storage on the generation side of the grid, creating a more reliable system (Figure D-2 below). The level of desired reliability can be chosen by the consumer (i.e., AFB) with the appropriate selection of generators and amount and type of associated storage.[152]

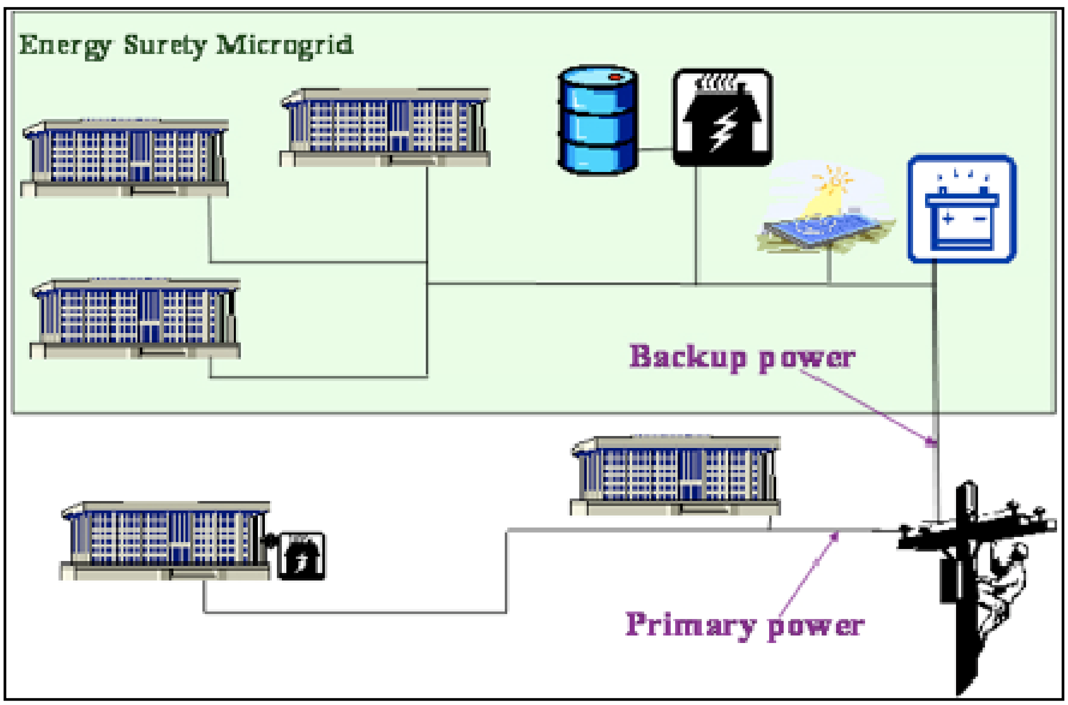


Figure D-2. Micro-Grid Systems Can Help Manage the Intermittency of Renewable Energy Sources.[153]

More specifically, the ESM is a well-defined approach to meeting these energy security needs and overcoming the limitations of radial one-way flow of power, single feeder lines from

151 Lasseter & Paigi, 2004, and Lasseter & Paigi, 2006.
152 Boyes & Menicucci, 2007.
153 *Ibid.*

the electric power grid, diesel generators for back-up power, no way to deal with extended power outages, single feeder lines from the natural gas pipelines, no natural gas storage on base, and integration of renewables with energy storage.[154] Within the framework of the ESM model, a number of requisites have been identified for an energy system with high levels of surety and are listed below:[155]

- Reducing the number of single points of failure,
- Generating the energy as close to the load as possible,
- Running generators full time,
- Using proven technologies,
- Varying the generation mix with renewables and other advanced distributed generation,
- Securing the fuel supply, and
- Appropriate on-site fuel/energy storage.

A micro-grid appears to meet these basic requirements when the micro-grid concept refers to a subset of the grid, in which distributed generators supply power. The ESM is designed to meet the essential factors noted above. While the ESM is interactive with the local utility grid and its generators share power delivery to the entire installation, it can isolate itself from the grid and provide power to mission-critical facilities, on its own, should the grid fail for any reason. In effect, the on-site generators become the primary sources of power for the buildings within the surety zone and the grid becomes the back-up energy source. In addition, depending on its design, it can meet the requisites for an energy system with high levels of surety. Some of the most important tasks involved in developing the Energy Surety Microgrid include:

- Develop surety requirements (i.e., determine what facilities to protect, the level of protection and the type of generators),
- Optimize the amount of fuel/energy storage,
- Properly control the surety microgrid,
- Model and measure the microgrid's effectiveness, and
- Ensure proper interconnection to the grid.

These tasks and required technologies are discussed in greater detail below.

D.2 Capabilities and Payoffs

The military is interested in the secure micro-grid concepts because there is a growing awareness of the defense mission's dependence upon the energy infrastructure and the vulnerability of that infrastructure to natural and man-made disasters.[156] ESM is a direct result of the need for increased energy security and decreased dependence on fossil fuels as the two major

154 Hatziargyriou et. al., 2007; Kwasinski & Krein, 2006; and Firestone & Marnay, 2005.
155 Menicucci, Ducey, & Volkman, 2006.
156 Menicucci, Ducey, & Volkman, 2006.

objectives of the new Army Energy Strategy for Installations. Both goals suggest that the Army consider diversifying its current use of the local electric utility for primary power and engine-driven generators for emergency back-up power. They also call for including renewable energy systems such as wind, solar, geothermal, and biomass, and other advanced distributed generation technologies such as fuel cells and micro-turbines. Increased energy reliability and security and, therefore, enhanced mission readiness, can be achieved by networking these power systems together in an "intelligent" micro-grid. This concept is built on the philosophy that, "the whole is greater than the sum of its parts."[157]

To assess the ESM's potential for Army use, the US Army Engineer Research and Development Center (ERDC) is working with the Assistant Chief of Staff for Installation Management, Installation Management Agency Headquarters, and the Research and Development Engineering Command. ERDC is investigating how the ESM concept can be implemented, not only at the installation and remote training facility level, but at forward base camps, tactical operation centers, and Soldier power—in other words, "home station to foxhole." ERDC's Construction Engineering Research Laboratory (CERL) and its Army partners are joined in this effort by Department of Energy (DoE) laboratories, Sandia National Laboratories in particular.[158] Presently, the results of this work are being implemented at Fort Sill under direction by CERL. These techniques are also being applied to Maxwell AFB to determine the appropriate ESM for their requirements.

Relative to the Air Force (AF) needs, the first step in implementing an ESM is to perform an energy and infrastructure assessment which can begin with the AF Critical Infrastructure Program (CIP). The AF CIP, established 5 years ago, has many of the ingredients needed. Included is a systematic procedure to identify discrete critical assets in the context of all threats and hazards; define requirements to assure ability to execute mission; identify and manage the risks that impede achieving those requirements, including mission dependencies inside and outside the fence line. To be more specific, Department of Defense Instruction 4170.11 (*Installation Energy Management*, dated 22 Nov 2005, paragraph 5.2.3) directs the Military Departments to:

- Take necessary steps to ensure the security of energy and water resources,
- Conduct Vulnerability Assessments, mitigate risks, and investigate off-base utility systems,
- Incorporate identified vulnerabilities into established Critical Asset Assurance Programs, and
- Invest in Renewable energy sources and distributed energy systems, including off-base systems, if economical.

The ESM assessment goes beyond the AF CIP by performing trade-offs between safety, security, reliability, sustainability, and economics to design the required mix of energy supplies and required infrastructure. In particular, renewable and other energy supply options are considered in the context of mission critical facilities that may supply increased energy security. This may take the form of multiple levels (including nested levels) of physical and cyber security depending upon the mission critical requirements. This approach enables the primary power

157 Ducey & Goran, 2007.
158 Tatro et. al., 2005.

generation being located on the base and using the grid as back-up power which leads to the option of "islanding" the base, if necessary. Also, the ESM provides the option to develop an integrated National Secure Electric Power Grid System that locates some portion of the nation's power generation systems on AFBs to increase the security (both physical and cyber), reliability, and resiliency of the overall national electric power grid (Table D-1 below).

Technology	Attributes	Siting Consider-ations	Energy and Power Reqts	Grid Integration Consider-ations	Maturity Level
Assessment Tools: Teams Software	In the field In development	Data base reqts	Trans. vs. Dist.	State/Local considerations	Available In Development
Storage: Fuel Batteries Capacitors Thermal	Mainstay/ reliable Rechargeable/ reliable High power Heat storage/ timing	Req. Tanks Flexible Flexible Req. Tanks	Scalable Limited Limited Scalable	Simple Simple/limited Simple/limited Costly	Standard/Mature Mature but limited Limited by app. Mature/New
Power Electronics: Low power High power High Temp. Inverters Bi-directional	Standard hardware Limited options In Development Scalable In Development	Standard Ltd/Simple Ltd/Simple Distribution In Development	Scalable Limited Limited Scalable Limited	Simple Limited Limited Scalable dist. In \Develop.	Standard/Mature Mature options In Development Scalable In Development
Control Algorithms: Open Loop Centralized Decentra-lized Agent-based	Standard/Manual Automated In Development In Development	Subject to State and Local Rules and Regulations	Today Limited Need to be scalable	Simple/limited Limited ops. In Develop. In Develop.	Standard/Mature Mature options In Development In Development
Sensors, Comms, Processing	Advanced Meters, Wireless Comm., Standard Boards	Subject to National, State and Local Rules and Regulations.	Need to be scalable	Available, but not designed for grid ops; Need to be scalable	Mature for general purpose; Maturing for grid applications

Table D-1. Summary of the Basic Technologies Needed for an Energy Surety Microgrid.

Examples of micro-grid products include the General Electric (GE) Global Research Microgrid. DoE and GE co-fund a two-year, approximately $4M microgrid effort led by GE Global Research. GE aims to develop and demonstrate a microgrid energy management (MEM)

framework for a broad set of microgrid applications that provides a unified controls, protection, and energy management platform (Figure D-3 below).[159]

At the asset level, MEM is intended to provide advanced controls for both generation and load assets that are robust with respect to limited power resource environments. At the supervisory level, MEM will optimize the coordinated operation of interconnected assets in the microgrid to meet customer objectives such as maximizing operational efficiency, minimizing cost of operation, minimizing emissions impact, etc.; and is also intended to enable integration of renewables and microgrid dispatchability. The GE product does not directly address the additional surety metrics included in the ESM to date.

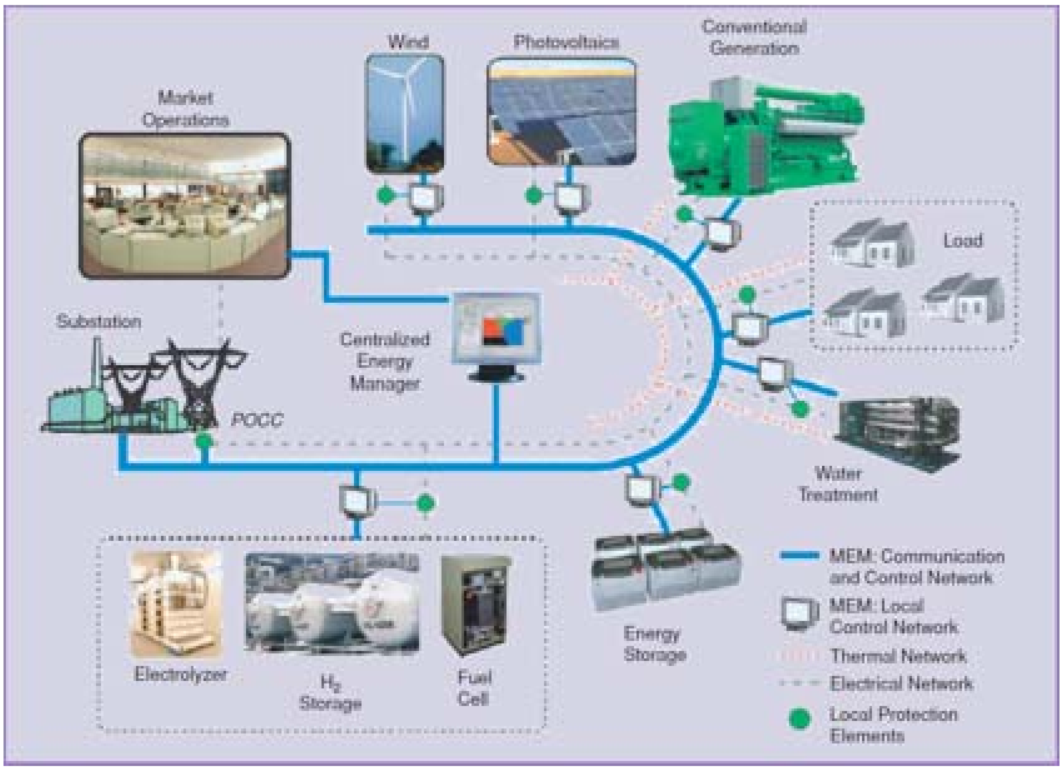


Figure D-3. Specific Elements of a Micro-Grid System.[160]

D.3 Concerns and Issues

Additional ties in the micro-grid distribution system may be incorporated to allow energy to be shared between local generation nodes, especially if the distribution system feeding in to the micro-grid is unreliable.[161] Currently, when power is interrupted, a building with a backup generator cannot share its energy with a neighboring building, even if the load in that building is of high priority. The ESM addresses this need by introducing intelligent control of resources and loads on the AFB side of the distribution system. Specifically, the ESM provides more small generation near the load, storage near the consumption points, and intelligently controlled micro-grids that integrate these resources into a system. This will provide the AFB with a viable

159 Hatziargyriou et.al., 2007 and General Electric Company, 2009.
160 Hatziargyriou et.al., 2007.
161 Bae & Kim, 2008.

alternative to the limited energy menu currently offered by utilities. Prototype ESMs can be built today using current generation and storage technologies, but with some limitations and constraints on operational flexibility. Advanced ESMs are expected to employ plug-and-play concepts allowing different generation and storage devices to be seamlessly removed and introduced into the system.[162] Energy storage is an important factor to the success of the ESM concept, and there are some practical limitations to today's storage technologies.

Before these limits are discussed, a brief recap is presented from Appendix A on the common storage technologies relevant to microgrids. For the purpose of ESMs, there are primarily three basic types of storage: fuel, thermal, and electrical. Fuel storage is quite common especially on the generation side in the form of fuel tanks, both above- and below-ground, that are ubiquitous on AFBs. Thermal storage is also quite common since nearly every home or commercial building has a store of hot water in a water heater. Some large buildings store heat or chilled fluid to heat or cool buildings when conventional systems are not available or when the price is high. Both fuel and thermal storage systems are well developed, relatively inexpensive, very reliable, and commonly available. These technologies can be easily integrated into an ESM.

On the other hand, the situation with electricity storage is quite different. As described in Appendix B, electric energy can be stored in electrochemical devices (e.g., batteries), electrostatic devices (e.g., capacitors), mechanically in flywheels, and possibly in the form of hydrogen for fuel cells. Capacitors are used extensively in the electrical industry for very short-term storage and for rapid discharge (high power applications) as well as to improve power quality where short term transients are encountered.[163]

Batteries are the mainstay for electric energy storage in today's electrical systems, and one can expect that to continue in the near future. Through a process of electrochemical reactions involving certain chemicals and metals, batteries can produce a steady stream of electrical energy. The most common batteries, such as the ones in cars, produce large amounts of electrical energy for a short period of time in order to start engines. However, batteries in stationary applications, such as those in a micro-grid, must supply lower levels of electrical energy for a longer period of time. These are less common, but are most often found in uninterruptible power supply systems. Usually coupled to a diesel generator, the uninterruptible power supply is activated during a power outage and uses the battery to supply power for critical building loads during the time that the generator is firing up and coming online. Many of these types of applications would be incorporated into an ESM.[164]

Battery storage is an excellent companion for intermittent generators (solar or wind) that might be found in an ESM. Energy stored at times of high production can be used when the renewable resource is not available. Storage can also supplement temporary decreases in output caused by variations in the wind or passing clouds, giving the renewable generators a more predictable output. There is much additional work needed to fully incorporate the various storage devices, especially advanced ones, into an ESM.[165]

A number of problem areas exist for the development and implementation of storage into an ESM. First, methods for optimizing the storage components (fuel, thermal, and electric) and

162 Menicucci, Ducey, & Volkman, 2006.
163 Boyes & Menicucci, 2007.
164 Abdallah et. al., 2006.
165 Menicucci, Ducey, & Volkman, 2006.

tying them to the surety metrics have not been fully vetted in deployed systems or developed into an automated software package. Questions remain about how much of the various kinds of storage should be included in an ESM to meet certain surety requirements. The problem is compounded by difficulties in quantifying some of the surety elements. Sandia National Laboratories is teaming with the Army's Construction Engineering Research Laboratory, New Mexico State University, and the University of New Mexico to address this challenge. Second, the best methods for controlling the storage devices on the ESM are not known with certainty. A consortium sponsored by the Consortium for Electric Reliability Technology Solutions which includes the University of Wisconsin, Sandia National Laboratories, and American Electric Power, have created basic micro-grid control systems to maintain reliable operation in a reasonably controlled environment. However, the Panel believes that additional control system sophistication is needed to apply advanced generation storage devices effectively within an ESM concerned with five fundamental surety elements. The Panel envisions that an ESM should be capable of dynamically changing its operational features while serving loads. Properly controlled storage devices are an essential feature to maintain power stability on an ESM. Third, technical, economic, and regulatory challenges remain. Many regulatory systems do not have provisions for including energy storage in a utility's rate base, preventing utilities from installing energy. Fourth, while fuel and thermal storage is relatively inexpensive, electrical storage costs remain relatively high. Research and development in both the private and government sectors is striving to improve the performance of storage and micro-grid products and bring down capital and operating costs to allow more market penetration to occur.[166]

Finally, with the exception of tanks that store fuel and lower-temperature thermal liquids, as well as ordinary batteries used mostly for motive power, advanced energy storage systems lack the extensive field experience needed to secure the confidence of surety micro-grid designers. Advanced thermal technologies, such as molten salt, have only been demonstrated in limited settings. New electric storage technologies are also lacking in the number of systems successfully demonstrated.

In addition, the existing open loop and centralized control systems can be used to begin the implementation of ESMs to meet the energy security requirements of AFB critical missions. Advanced agent-based decentralized control systems will be required to develop a truly "plug-and-play" ESM that can be taken to the field within forward base operations.

166 *Ibid.*

Appendix E: Air Force Documents and Energy Usage

This Appendix provides the energy documentation and relevant reports provided to the Panel by various Air Force (AF) Civil Engineering organizations.

AF Base Energy Drivers

- **Mandates**
  - **EO 13423: 30% reduction in energy consumption by 2015**
  - **Energy Independence & Security Act of 2007 (EISA), for all new and renovated buildings:**
    - **55% reduction in fossil-fuel generated energy consumption by 2010**
    - **100% reduction in fossil-fuel generated energy consumption by 2030**
- **Costs**
  - **Air Force energy costs have doubled since 9/11/2001**
  - **Every $10 increase in the price of a barrel of oil increases the AF bill by $500M**
  - **Fully burdened cost of fuel in forward operating bases estimated at >$400/gal (DSB 2001 study)**
- **Security**
  - **AF relies on commercial sources for resilient, reliable energy distribution capability**
  - **Reliance on diesel generator backup is dependent on fuel supply lines**

PRIOR STUDIES: Did not, or only partially addressed security

Figure E-1. AF Base Energy Drivers.

Air Force bases are held to energy efficiency standards that have been directed by a variety of statutory and policy mandates. The major mandates that are driving AF base energy management include:

- Executive Order 13423 "Strengthening Federal Environmental, Energy and Transportation Management"
- Energy Independence and Security Act (EISA) of 2007
- Energy Policy Act of 2005 (EPAct 2005)
- Air Force Policy:
  - o Air Force Energy Program Policy Memorandum 10-1 (AFEPPM10-1)
  - o Air Force Policy Directive (AFPD) 23-3 "Energy Management"

Executive Order 13423

- "Strengthening Federal Environmental, Energy and Transportation Management"
- Federal Facilities Provisions:
  - Energy Reduction Goals - 3% per year or 30% by FY 2015
  - At least half of required Renewable Energy must be from sources placed in service after Jan 1, 1999. Counts thermal as well as electrical energy. (Allows non-electric.)
  - Limits the use of Renewable Energy Credits (RECs) to 50% of the goal--you can't "buy yourself out"
  - Implement renewable energy generation projects on agency property for agency use
  - Water consumption intensity reduced 2% annually or 16% by FY 2015 - begins 08
  - New construction and major renovation follow 2006 High Performance Bldg MOU
    - Designed for Energy Star targets and 30% better than ASHRAE 90.1-2004.
    - Renovations 20% better than 2003 baseline
    - Install building level meters in all construction and major renovation
    - 20% less potable water use than baseline after meeting EPAct 1992 requirements
    - 50% reduction in outdoor water use from conventional means
    - Achieve minimum 2% daylight factor in 75% of space for visual critical tasks
  - 15% of existing inventory incorporate above guidelines by end of FY 2015
  - 100% of new designs
- Revokes EO 13123

Figure E-2. Summary of Executive Order 13423.

Executive Order (E.O.) 13423, Strengthening Federal Environmental, Energy, and Transportation Management, was signed on January 24, 2007, to strengthen key goals for the Federal Government. It set more challenging goals than the EPAct 2005 and superseded E.O. 13123 and E.O. 13149. E.O. 13423 requires federal agencies to reduce energy intensity by 3% each year, leading to 30% by the end of fiscal year (FY) 2015 compared to an FY 2003 baseline. This goal was given the weight of law when ratified by EISA 2007.

The Air Force is reducing energy intensity as demonstrated in the US Air Force 2008 Energy Almanac, Volume 1 (EA08V1), which includes detailed energy consumption and cost data as well as metrics which help measure progress toward the E.O.13423 goal. The goal for FY08 was a 9% reduction in energy intensity from the FY03 baseline. As a whole for FY08, the Air Force had a 16.8% reduction in energy intensity. Total energy consumption in FY08 was 64,749,505 million British Thermal Units (MBTU), a reduction of 6,058,114 MBTUs from the FY03 baseline. (Reference: Air Force Energy Almanac, prepared by the Energy Center, Headquarters Air Force Civil Engineer Support Agency, Tyndall AFB, FL. Almanac data was imported from the Air Force's Defense Utility Energy Reporting System report titled "Cumulative Percent Reduction Report").

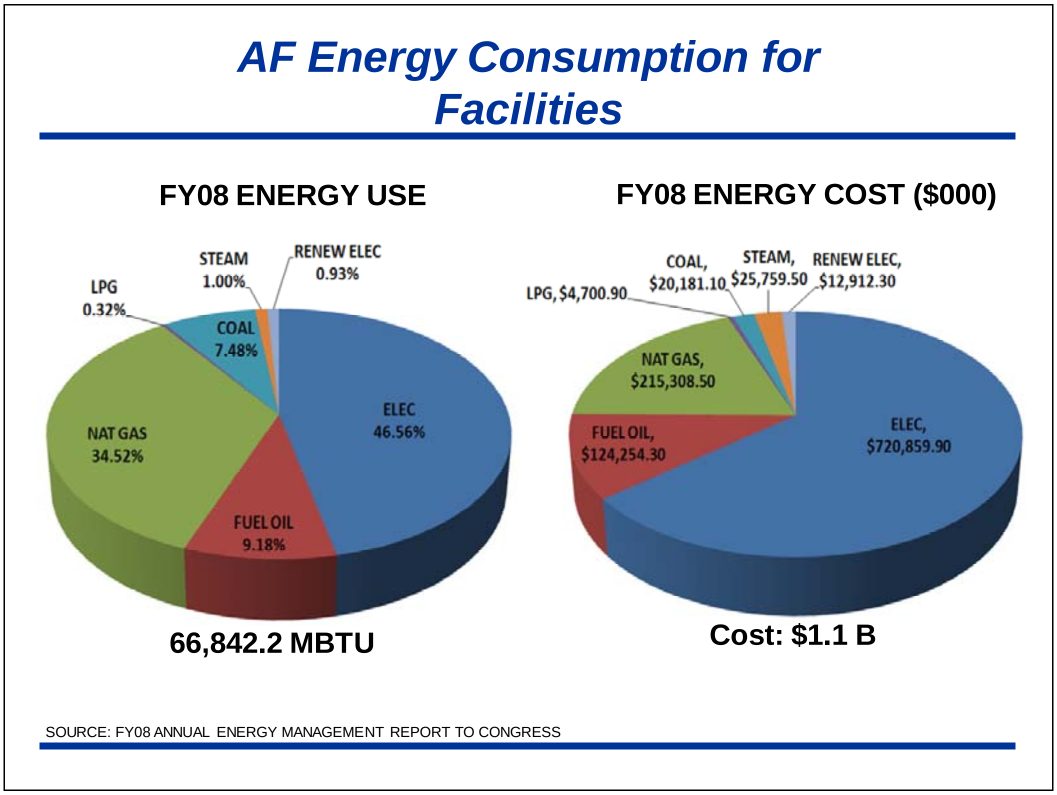


Figure E-3. AF Energy Consumption and Cost for FY08.

As demonstrated above in Figure E-3, energy use cost the Air Force over $1 billion in FY08. Within facilities, electricity is expensive: it accounts for 47 percent of total facility energy used, but disproportionately represents more than 65 percent of utility cost (Figure E-3). By comparison, natural gas represents 34.5 percent of consumption, but only 20 percent of cost. The remainder of facility energy comprises fuel oil, coal, steam, hot water, liquid propane, and renewable electricity. From FY03 to FY08 utility costs have risen by 29 percent despite an 8.6 percent reduction in total consumption. This has occurred as a result of increases in the average unit price of energy. These consumption and cost charts indicate that different strategies will be necessary within facility operations to achieve the energy reduction and cost savings goals mandated by both federal law and Air Force policy. A focus on reducing the amount of purchased electricity will have the largest impact on energy costs.

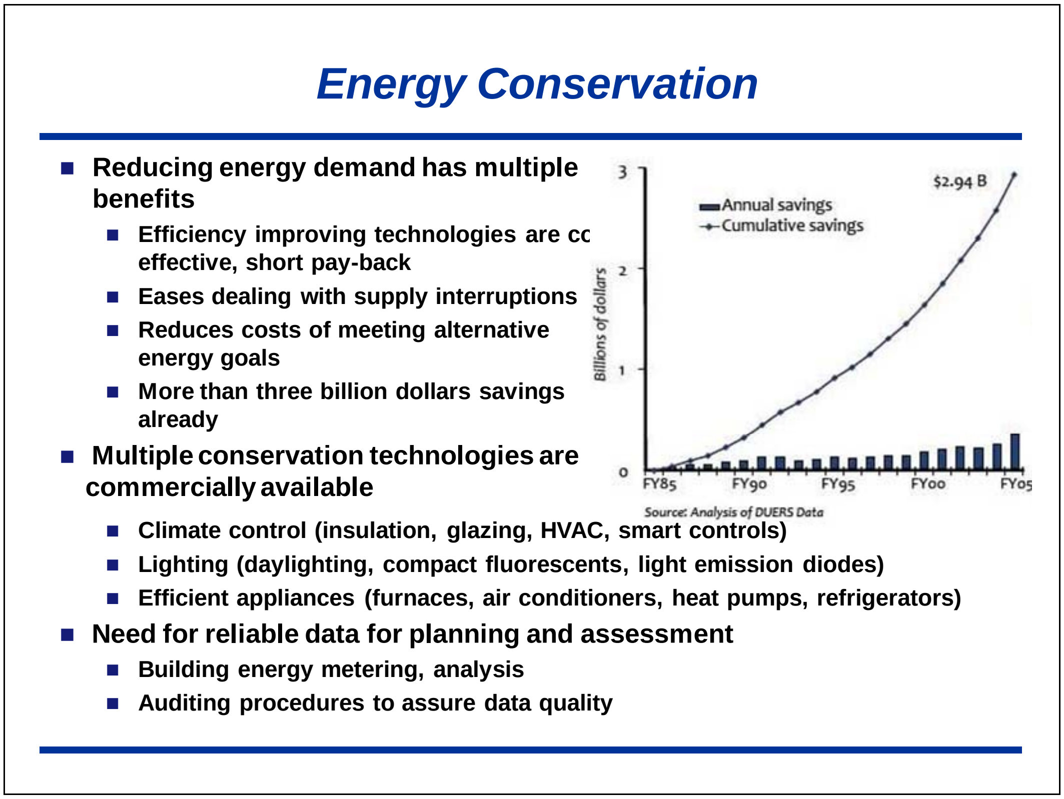


Figure E-4. Benefits of Energy Conservation.

Energy Conservation Overview

Reduction of base energy demand through conservation measures provides multiple benefits.

1) Most conservation measures are cost-effective in that reduced energy costs provide payback on investments over a short period (a few years).
2) The Energy Policy Act of 2005 provides that saved appropriated energy funds may be retained by the agency involved.
3) Reduced demand eases dealing with supply interruptions.
4) Reduced demand reduces the investments required to meet alternative energy goals.

The Air Force has initiated an aggressive conservation program to reduce base energy consumption, which through 2005 has produced energy cost savings of nearly three billion dollars.[167]

Policy Background

The Energy Policy Act of 2005 requires federal energy savings of 20% from a FY 2003 baseline to be achieved by FY 2015.

167 Air Force Facility Engineer Center, 2008.

Energy Policy Act of 2005

Energy Management Requirements (Sec. 102). The baseline for federal energy savings is updated from FY 1985 to FY 2003, and a new 20% reduction goal is set for FY 2015. By the end of 2014, DoE is to assess progress and set a new goal for FY 2016 through FY 2025. Standards for exclusion are set, which empower DoE to exempt, under certain conditions, buildings that serve a national security function or for which achieving the target would be impracticable. Further, agencies are allowed to retain appropriations for energy expenses that are saved by the energy efficiency measures. A report to Congress is required.

Further, President Bush issued E.O. 13423 in 2007, which requires an annual reduction in energy intensity (energy consumption per unit building area) of 3% per year from a FY 2003 baseline, to reach 30% by the end of FY 2015.

Executive Order 13423 (2007)

Sec. 2. ***Goals for Agencies***. In implementing the policy set forth in section 1 of this order, the head of each agency shall: (a) improve energy efficiency and reduce greenhouse gas emissions of the agency, through reduction of energy intensity by (i) 3 percent annually through the end of fiscal year 2015, or (ii) 30 percent by the end of fiscal year 2015, relative to the baseline of the agency's energy use in fiscal year 2003;

Air Force Base Energy Data

The United States Air Force (USAF) Energy Almanac (FYs 2006, 2007, and 2008) reports energy data at the base level including the FY03 baseline for reduction mandates. These data are summarized by command and for the entire USAF. Tabular and graphical data include energy consumption, costs, and building inventory (square feet). Total energy less mobility energy less renewable energy defines "reportable energy." Mobility energy refers primarily to energy used in flight simulators. Renewable energy "consumption" is in reality purchased renewable energy credits (RECs), primarily for wind energy. The Air Force currently buys RECs at an annual rate of about $75 million (based on September 2007 purchase, the latest available data).[168] Calculated energy intensities (Btu/ft^2) provide data needed to demonstrate compliance with E.O. 13423. A summary of progress to date appears in the following figure:

168 United States Air Force: USAF Energy Almanac FY 2007, Volume VII.

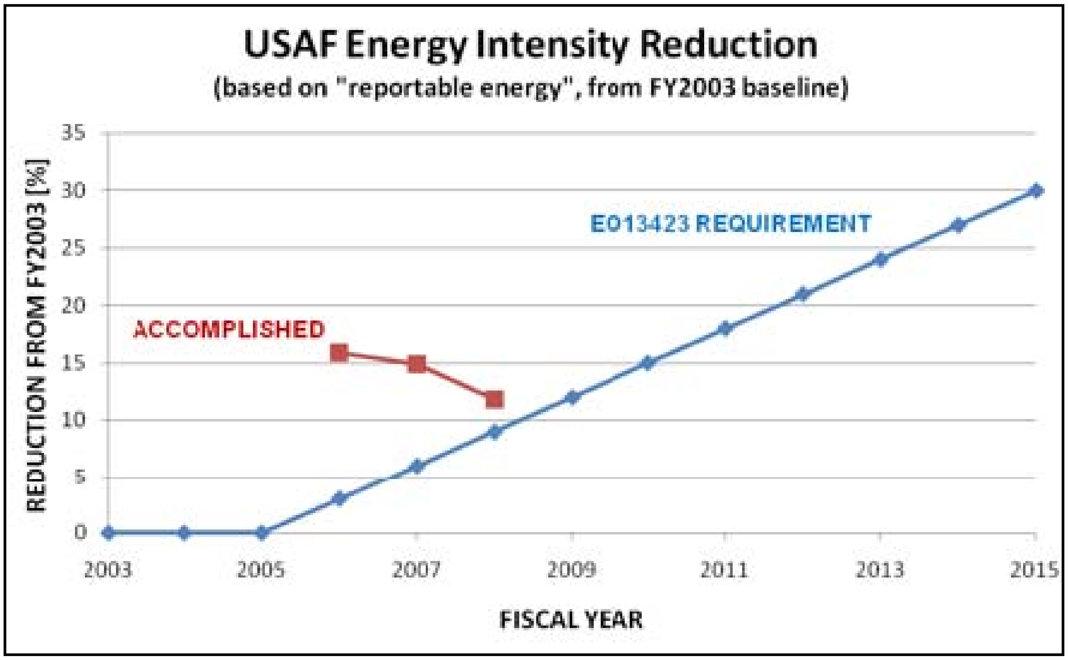


Figure E-5. USAF Energy Intensity Reduction Based on Data in AF Energy Almanac for FY 2006, 2007, and 2008.

A better metric to judge the effectiveness of building energy conservation progress would be the total energy less the mobility energy as the purchased renewable energy credits play no role in reducing base energy consumption or in reducing energy intensity. However, at this time the magnitude of these credits are not sufficient to affect significantly the energy intensity assessment.

The reason for the lack of progress over the first three years is not clear and may not be real. FY06 data are incomplete, covering only about one-sixth of all installations (by building area). It may be that year-to-year changes are dominated by variation in weather, related to changes in the FY03 baseline that was adjusted in both FY07 and FY08 for transfer of military family housing to private ownership, or other data issues. Reliable, audited data are essential to the assessment of the effectiveness of the conservation program.

These data are not consistent with those reported for EISA requirements, Figure E-6. EISA reporting allows exclusion of some facilities and double counting of renewable energy. Reconciliation of the differences between Figures F-5 and F-6 is not clear.

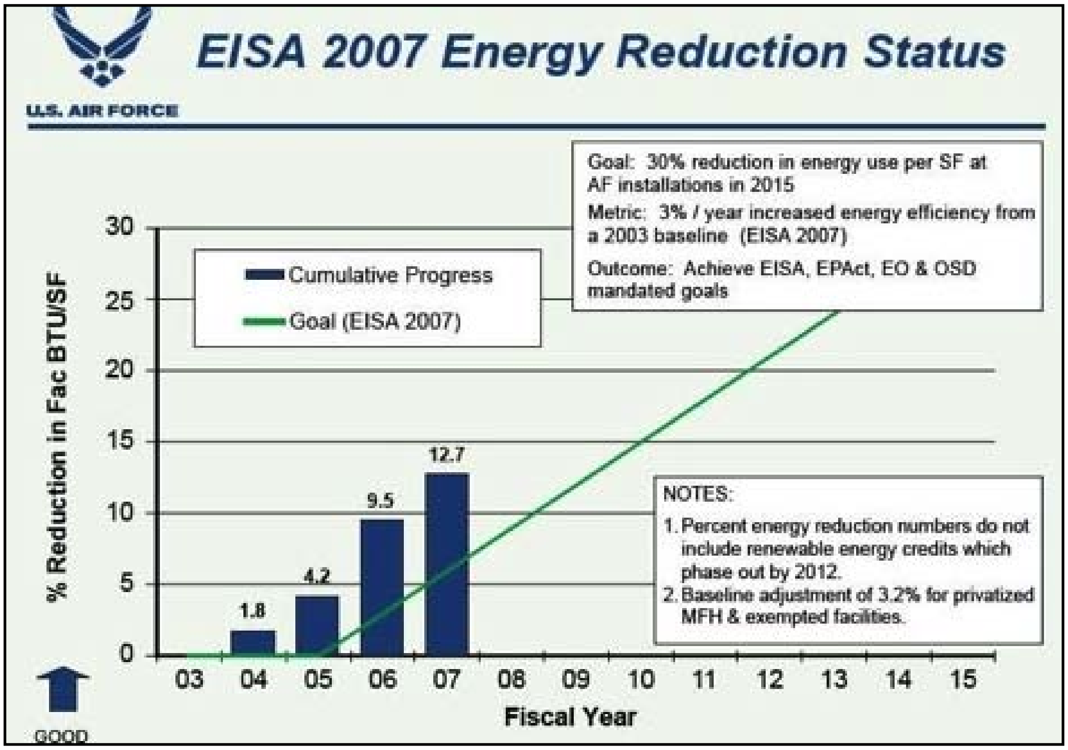


Figure E-6. AF Energy Intensity Reduction as Reported for EISA Purposes.[169]

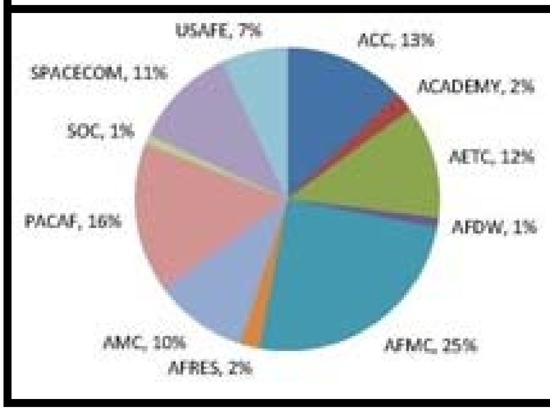
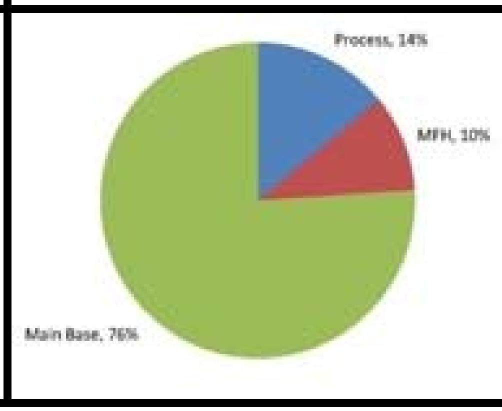
FY2008 Facility Energy Use at Major Commands	FY2008 Facility Energy Use, USAF
	

Figure E-7. AF Energy Use by Command and by Function.[170]

Main base ("industrial") energy use dominates Air Force building energy consumption (Figure E-7 above). "Process" energy consumption is dominated by the AF Material Command, particularly Tinker AFB, and presumably is related to energy-intensive overhaul activities. Continuing privatization of military family housing will reduce direct Air Force responsibility

169 Air Force Facility Engineer Center, 2008.
170 United States Air Force: USAF Energy Almanac FY 2008, Volume I.

for and direct control of energy usage in this sector. There may be an opportunity to condition the privatization and operation of housing for military personal to include energy conservation.

Conclusions

Conservation through reducing demand is the most cost-effective approach to meeting energy needs. An aggressive program of improving energy efficiency of buildings should be continued and expanded. Reliable, audited energy consumption data are essential to implementing and assessing conservation programs.

Energy Independence
and Security Act (EISA) of 2007

- **Codifies the EO 13423 3% annual energy reduction or 30% by 2015 (section 431)**
- **Reduce the use of fossil fuels in new and renovated buildings by 55% in 2010, increasing to 100% in 2030 (433)**
- **'Beginning in FY 2010 each agency shall reduce petroleum consumption and increase alternative fuel consumption so as to by Oct 1, 2015, and each year thereafter, achieve at least a 20% reduction in annual petroleum consumption and a 10% increase in annual alternative fuel consumption from the 2005 baseline' (142)**
- **Allows sale of excess renewable energy (515)**
- **Energy and water evaluations for 25% of facilities annually and all appropriate facilities on 4 year cycle (432)**
- **Energy and water conservation measures be entered and annually updated in a "to be created" web based tracking tool (432)**
- **Metering data entered into a web based benchmarking database (432)**
- **OMB to issue scorecards (432)**
- **Adds cogeneration and heat recovery, and water conservation as "energy savings" for ESPC. Does not specify renewable energy (515)**
- **DoE to identified a federal green building certification system (433)**
- **Large capital investments must be the most energy efficient design that is life cycle cost effective. Process in place by July 08 (434)**
- **Adds Natural Gas and Steam metering requirements by Oct 2016 (434)**

Figure E-8. The Energy Independence and Security Act of 2007.

The Energy Independence and Security Act of 2007 established energy management goals and requirements while also amending portions of the National Energy Conservation Policy Act (NECPA). It was signed into law on December 19, 2007. One of the key requirements of EISA 2007 is section 433, which requires a reduction in fossil fuel-generated energy in federal buildings. The conservation technologies outlined in the above slides provide opportunities for the Air Force to meet the energy reduction goals identified in EISA 2007. By combining conservation technologies with alternative energy sources, the Air Force will continue to remain on track for meeting the goal of a 100% reduction in the use of fossil fuels in new and renovated buildings.

Energy Independence & Security Act (EISA) of 2007

- **Federal Building Energy Efficiency Performance Standards, Sec 433. New federal buildings (> $2.5M) will be designed so that the fossil fuel-generated energy consumption of the buildings is reduced" (from a 2003 baseline):**

FY	%Reduction
2010	55
2015	65
2020	80
2025	90
2030	100

Where will we get the energy savings?

Figure E-9. Section 433 of the Energy Independence and Security Act of 2007.

Section 433 of EISA 2007 directs the Department of Energy (DoE) to issue revised federal building energy efficiency performance standards within one year of its enactment. The revised standards specify that buildings shall be designed so that the fossil fuel-generated energy consumption of the buildings is reduced, as compared with such energy consumption by a similar building in FY 2003 (as measured by Commercial Buildings Energy Consumption Survey or Residential Energy Consumption Survey data from the Energy Information Agency), by the percentage specified in the above table.

Implementation of these aggressive goals will require a coordinated effort to ensure that military construction projects are adequately funded to incorporate both alternative energy and conservation technologies into all future designs.

Energy Policy Act (EPAct) of 2005

The Energy Policy Act of 2005 established a number of energy management goals for federal facilities and fleets. It also amended portions of the NECPA. EISA 2007 and E.O. 13423 update many of the energy management requirements of EPAct 2005. Key renewable energy requirements of EPAct 2005 are still in effect and include:

- Defines "renewable energy" as electric energy generated from solar, wind, biomass, landfill gas, ocean (including tidal, wave, current, and thermal), geothermal, municipal solid waste, or new hydroelectric generation capacity achieved from increased efficiency or additions of new capacity at an existing hydroelectric project.

- Requires the Secretary of Energy to ensure that, to the extent economically feasible and technically practicable, the following amounts of the total electricity consumed by the Federal Government come from renewable energy:
    - Not less than 3% in FYs 2007-2009
    - Not less than 5% in FYs 2010-2012
    - Not less than 7.5% in FYs 2013 and thereafter
- Provides a bonus to federal agencies by allowing them to double count renewable energy if it is produced on-site and used at a federal facility, produced on federal lands and used at a federal facility, or produced on Native American land and used at a federal facility.

Air Force Energy Policy Memorandum 10-1

Air Force Energy Policy Memorandum 10-1 was signed by the Secretary of the Air Force on December 19, 2008 with the purpose of immediately implementing the Air Force's Energy Policy as outlined in the Air Force Energy Strategic Plan.

The Air Force Energy Strategic Plan is structured to achieve the goals mandated by all public laws and Executive Orders governing the Air Force, including, but not limited to the EPAct of 2005 and E.O. 13423, as well as the mandates of the President and the Office of the Secretary of Defense. The overarching vision in the Air Force Energy Strategy is "Make Energy a Consideration in All We Do" and it is made up of three key components: *Reduce Demand*, *Increase Supply*, and *Culture Change*. Each of the components includes specific implementation goals as described below:

Reduce Demand:

- Reduce aviation fuel-use/hour operation by 10% (from a 2005 base line) by 2015.
- Implement pilot fuel efficiency measures in all standardization/evaluation flights by 2010.
- Incorporate pilot fuel efficiency elements in the Undergraduate Pilot Training (UPT) training syllabus by 2011.
- Reduce motor vehicle fleet petroleum fuel use by 2 percent per annum.
- Reduce installation energy intensity by 3 percent per annum

Increase Supply:

- Increase non-petroleum-based fuel use by 10 percent per annum in the motor vehicle fleet.
- Increase facility renewable energy use at annual targets of 5 percent by FY 2010, 7.5 percent by FY 2013, and 25 percent by FY 2025–50 percent of the increase must come from new renewable sources by 2016.[171]

171 The Air Force has set renewable energy goals that exceed those mandated by Congress. The Energy Policy Act of 2005 (EPAct 2005) requires a minimum of 5% renewable energy by 2012 and a minimum of 7.5% beginning in 2013 and thereafter. The Air Force has determined that it will increase

- Be prepared to cost competitively acquire 50 percent of the Air Force‘s domestic aviation fuel requirement via an alternative fuel blend in which the alternative component is derived from domestic sources produced in a manner that is greener than fuels produced from conventional petroleum.

Culture Change:

- Provide energy leadership through Energy Management Steering Groups.
- Train all personnel in energy awareness by 2010.
- Implement an energy curriculum in the Academy and the Air University by 2010.
- Communicate energy awareness at all installations during Energy Awareness Month each October.

The Air Force Energy Strategy implementation goal of a 3% reduction per year in energy intensity aligns with the Federal Facilities Provisions of E.O. 13423, Strengthening Federal Environmental, Energy, and Transportation Management and the Energy Independence and Security Act of 2007. Energy intensity is defined as energy use per gross square foot of facility space.

In order to meet this aggressive renewable energy goal, base energy managers will need training and resources that are not yet readily available.

Recommendation (1) *Adopt a systems approach to implement alternative energy at Air Force installations* recommends that the Air Force develop in-house competency while providing resources to Base Energy Managers to support implementation of alternative energy projects.

Air Force Policy Memorandum (AFPM) 10-1 identifies the Undersecretary of the Air Force (SAF/US) as the Air Force Senior Energy Official responsible for managing the Air Force Energy Program. In the absence of the Under Secretary, the duties were delegated to the Assistant Secretary of the Air Force for Installations, Environment, and Logistics (SAF/IE).

AFPM 10-1 refers to Air Force Policy Directive 23-3, “Energy Management” as the guiding document for the establishment of an Energy Management Steering Group (EMSG) at each level of command. The goal of the EMSG is to coordinate all energy matters within the applicable level of command (Air Force Headquarters, Major Command, and Installation).

The Energy Senior Focus Group serves as the EMSG within Headquarters Air Force and is shown below:

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facility renewable energy use at annual targets of 5 percent by FY10, 7.5 percent by FY13, and 25 percent by FY25.

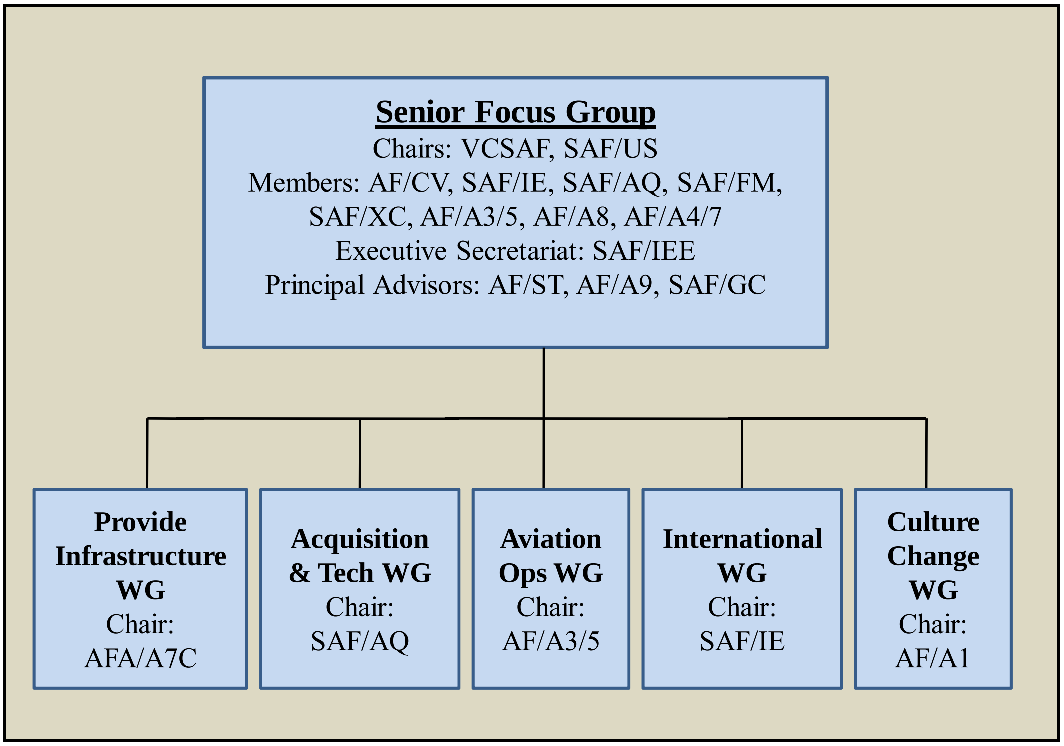

Figure E-10. Organization of the Energy Senior Focus Group.

The Energy Senior Focus Group (SFG) is co-chaired by the Undersecretary of the Air Force and the Vice-Chief of Staff of the Air Force (AF/CV) and includes senior members from HQ USAF offices. The Air Force Civil Engineer chairs the Provide Infrastructure Working Group and is responsible for tracking responsiveness to the Air Force Infrastructure Energy Strategic Plan. The Air Force Civil Engineer Support Agency (AFCESA) serves as an advisory member of the Energy Senior Focus Group.

AFPM 10-1 (Section 4, Roles and Responsibilities), identifies the specific energy responsibilities at each level of Air Force command. Paragraph 4.17 specifies installation energy responsibilities. Energy Security as an installation responsibility is outlined in Paragraph 4.17.1, which states that:

> Each base EMSG is required to determine the installation's vulnerability to energy interruptions… and to annually review all plans to ensure a description of actions to be taken to minimize potential impacts in response to a serious interruption of energy supply that may occur at the local, state, or national level. The plans must address vulnerabilities of Air Force missions and facilities due to natural disasters, major system failures, energy supply constraint disputes, and terrorist sabotage. These plans should identify types of energy critical to base operation, energy suppliers, alternative sources, and procedures for obtaining emergency supply. The assessment includes an indication of the extent of the delay that can be allowed for critical programs and operations as well as points at which the primary base mission can no longer be accomplished. Control and feedback mechanisms for managing an energy emergency situation should be

summarized in these plans. Base requirements should be coordinated with the local utilities and community disaster plans.

Although AFPM 10-1 addresses installation energy responsibilities in detail, the requirement to evaluate the vulnerability of Air Force missions and facilities to energy disruptions and take action to eliminate them was identified in Air Force Policy Document 23-3, Energy Management, dated 7 September 1993. In addition, Air Force Instruction (AFI) 10-211, *Civil Engineer Contingency Response Planning;* dated 22 September 2008 and AFI 10-2501, *Air Force Emergency Management Program Planning and Operations* dated 24 January 2007 both require the base Civil Engineer to develop plans and identify resources required to reestablish utilities or provide backup systems after an attack or disaster.

AFPD 10-24, *Air Force Critical Infrastructure Program (CIP),* dated 28 April 2006 provides a framework for identifying those assets and infrastructure that are critical to the execution of the Air Force mission. The CIP is a risk management/mission assurance program that assures the ability to execute the mission by identifying the impact of asset loss or degradation, determining the risk of loss through a risk assessment, and then identifying ways to manage the risk. Per AFPD 10-24, it is Air Force policy to:

- Assure the availability of infrastructure critical to readiness and operations in peace, crisis, and war.
- Establish and fund a comprehensive Air Force CIP fully integrated with DoD and National level programs to coordinate, develop, and implement strategy and policy associated with the identification, prioritization, assessment, and protection of critical Air Force cyber and physical infrastructures.
- Establish Air Force Sector Leads to foster partnerships with other government and civil agencies and the private sector to address critical infrastructure issues.
- Incorporate CIP education and training into all appropriate command and base level courses as well as courses for senior staff (military & civilian) and senior enlisted professional military education.
- Incorporate CIP into MAJCOM (Major Command) and installation level training exercises to instill an awareness of the impact caused by the loss of critical assets through the exploitation of their vulnerabilities.

AFPD 10-24 identifies the HQ USAF Deputy Chief of Staff, Air, Space and Information Operations, Plans and Requirements (AF/A3/5) as the office of primary responsibility for the central management and oversight of the Air Force’s CIP. This includes establishing a CIP Working Group comprised of Air Force Sector Lead representatives, Headquarters Air Force Advisors, as well as representatives from the Major Commands, Field Operating Agencies, Direct Reporting Units, and Air Force Component representatives from the Combatant Commands as needed. The CIP Working Group serves as the principal working-level forum to vet CIP-related strategy development, policies, procedures, plans and operations, and raise CIP-related issues.

The Air Force CIP is based on and directly supports National and DoD CIP guidance. Department of Defense Directive 3020.40, *Defense Critical Infrastructure Program*, dated 19 August 2005 states that it is DoD policy that:

- Defense Critical Infrastructure, which includes DoD and non-DoD domestic and foreign infrastructures essential to planning, mobilizing, deploying, executing, and sustaining US military operations on a global basis, shall be available when required. Coordination on remediation and/or mitigation shall be accomplished with other federal agencies, state and local governments, the private sector, and equivalent foreign entities, as appropriate.
- Vulnerabilities found in Defense Critical Infrastructure shall be remediated and/or mitigated based on risk management decisions made by responsible authorities.
- The identification, prioritization, assessment, and assurance of Defense Critical Infrastructure shall be managed as a comprehensive program that includes the development of adaptive plans and procedures to mitigate risk, restore capability in the event of loss or degradation, support incident management, and protect Defense Critical Infrastructure related sensitive information.
- The Defense Critical Infrastructure Program shall complement other DoD programs and efforts, such as: force protection; antiterrorism; information assurance; continuity of operations; chemical, biological, radiological, nuclear, and high-explosive defense; readiness; and installation preparedness—all of which contribute to mission assurance.

Although both Air Force and DoD CIP guidance are clear that the program will be supported and funded at all levels, actual implementation appears to be lagging.

In a briefing to the Study Panel, it was reported by the Headquarters AF Homeland Operations Office (AF/A3O-AH) that the current level of funding for the Air Force CIP supports a minimal number of assessments per year.

AF/A3O-AH recently completed a CIP assessment of critical infrastructure at nine Air Force installations and provided the results to this Study. Generalized findings and trends relative to the electrical infrastructure at the nine installations included the following:

- SCADA (Supervisory Control and Data Acquisition) systems not fully employed or in existence.
- Local power company doesn't have visibility of installation's substations/activities.
- Contingency/utility restoration/disaster response plans do not account for critical assets or facilitates housing critical assets.
- Transformers and certain power equipment at some sites are 30-40+ years in age.
- Redundant power feeds nonexistent or converge into one line, making it a single point of failure.
- Backup power generation systems in some cases were designed only for powering-down operations, not maintaining operations.
- Some substations outside installation have minimal physical security and have been subject to copper vandalism.
- Technical Control Centers were unable to handle electrical loads.
  - Increased temperatures, causing overheating of critical asset systems,

- HVAC (heat, ventilation, and air conditioning) systems incapable of cooling facility, and
- Temperature sensors too far away to register accurate readings.

- Some on-site substations did not have a fire suppression system or were not connected to base fire department.

In addition to the demonstrated findings of serious shortfalls in energy surety through the CIP assessments, an informal survey of seven individual Air Force bases, representing six major commands, was conducted at the request of this Air Force SAB. Of the seven bases queried, only two had energy vulnerability plans that addressed a long-term or "serious" interruption of the energy supply. Of the five installations that had no plans for a long-term outage, four had implemented fairly sizable renewable energy projects at their installations.

Recommendation (2): *Implement current policy guidance on energy security* was developed in response to findings that portrayed a lack of understanding or sense of urgency in implementing the policies at the installation level. Adequate policy guidance exists to address energy security; MAJCOMs should aggressively pursue implementation of the existing policies.

The Air Force CIP provides a vehicle to develop mission-critical priority lists and perform risk assessment of the energy infrastructure at Air Force installations. It should be adequately funded to provide an Air-Force wide analysis of critical energy infrastructure which would allow security to be integrated into all future alternative energy planning and prioritization activities. An installation assessment of the critical energy infrastructure would also assist base Energy Managers and Energy Management Steering Groups in developing vulnerability plans to address potential impacts of a serious interruption of energy supply, as required by AFPM 10-1.

The Air Force Infrastructure Energy Strategic Plan was published in 2008 as a guide for meeting federal energy mandates. Where the Air Force Energy Strategy outlined in AFPM 10-1 is comprehensive and includes the full spectrum of Air Force energy activities across all operational and support areas, the Air Force Infrastructure Energy Strategic Plan focuses on infrastructure, ground vehicles, ground fuels, and equipment.

The Air Force Infrastructure Energy Strategy (Figure E-11 below) is demonstrated in a conceptual framework of four energy pillars, supported by three enablers, above a foundation of two transformational concepts. The four energy pillars are:

- Pillar 1 – Improve Current Infrastructure
- Pillar 2 – Improve Future Infrastructure
- Pillar 3 – Expand Renewables
- Pillar 4 – Manage Cost

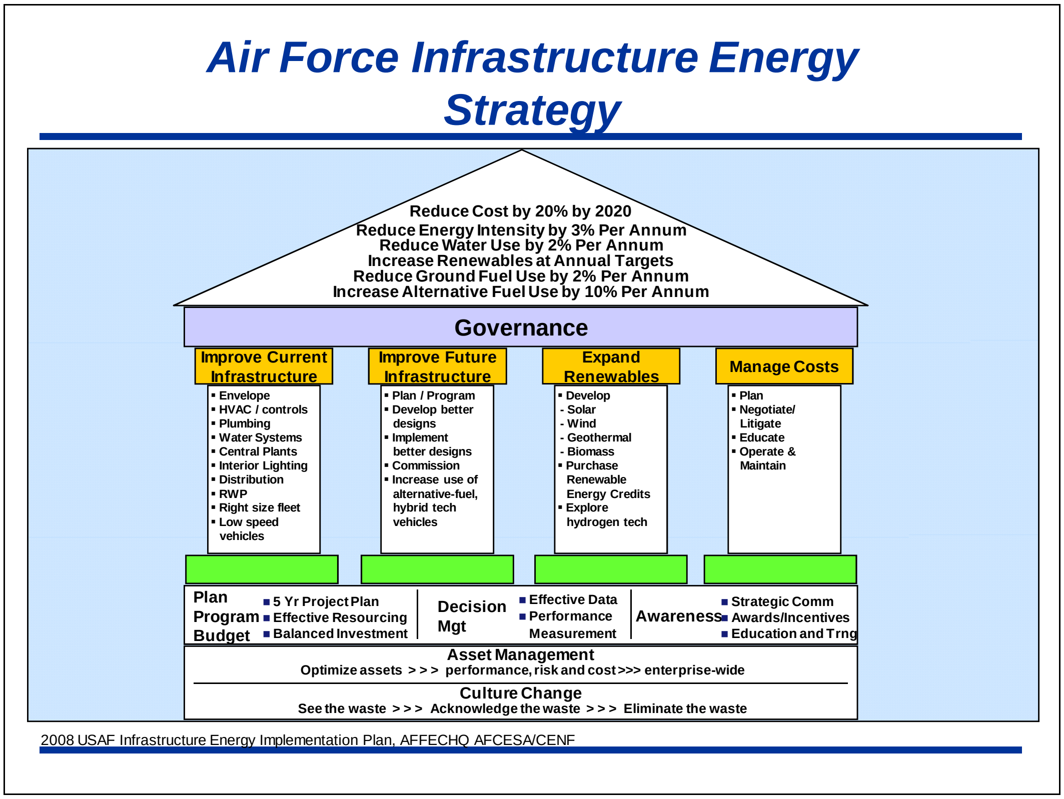

Figure E-11. The Air Force Infrastructure Energy Strategic Plan.

Supporting these pillars are three enablers: Planning, Programming, and Budgeting; Decision Management; and Energy Awareness. The transformational concepts at the foundation of the strategy are Asset Management and Culture Change. The infrastructure strategic plan identifies specific objectives; estimated completion dates; and offices of primary responsibility for each of the four pillars and three enablers.

Also included in the Air Force Infrastructure Energy Strategic plan is a description of the governance structure for infrastructure energy matters in the Air Force, beginning with the Senior Focus Group as identified in AFPM 10-1.

Senior Focus Group

As the senior energy management steering group, the SFG's scope extends to all energy use and conservation issues within the Air Force, including seeking alternative energy opportunities, at all Air Force installations, within ground transportation and support equipment/systems, aviation fuel use, and associated science and technology opportunities. The SFG is chaired by the Department's Senior Energy Official, the Assistant Secretary of the Air Force for Installations, Environment, and Logistics (SAF/IE). Infrastructure Energy issues are governed by the Provide Infrastructure Working Group (PIWG), which is chaired by the Air Force Civil Engineer (HQ USAF/A7C) and acts as the conduit to the SFG for MAJCOM infrastructure energy policy and initiatives.

Provide Infrastructure Working Group (PIWG)

The PIWG addresses facilities, infrastructure, ground vehicles and equipment, and ground fuels initiatives, and reports to the SFG. The PIWG is the advocate for MAJCOM initiatives and resource requirements though the corporate process. It links base-level EMSG priorities through the respective MAJCOM steering group to advocacy at the corporate Air Force level. The PIWG is chaired by the Air Force Civil Engineer (HQ USAF/A7C) with functional representation spanning the full scope of the Infrastructure Energy Strategy.

Energy Management Steering Group (EMSG)

The EMSG is a cross-functional working group comprising mission owners and subject-matter experts, in areas such as aviation, logistics readiness, vehicles, ground fuels, communications, public affairs, and facilities engineering. It sets the tone of the energy program; provides command emphasis and direction; develops initiatives, ideas, and potential strategies; and further develops command policy, guidance, and execution strategies. Membership and leadership of the EMSG is at the discretion of the Major Command and installation commander. Representatives from all major energy managing activities, including civil engineering, public affairs, transportation operations, budget, aircraft maintenance and operations, logistics, and fuels management are members of a Major Command or installation level Energy Management Steering Group. The EMSG provides a forum for coordinating energy activities and for conducting the Air Force Energy Strategy.

Base Energy Manager

The Base Energy Manager is responsible for coordinating a semi-annual meeting of the Wing Energy Management Steering Group as part of the overall requirement to "Manage the Base Energy Program." The Base Energy Manager also: oversees energy program development; coordinates energy maintenance activities; provides guidance on sustainable design and energy master planning; coordinates installation energy security assessments; develops the installation renewable energy strategy; develops water conservation strategies; conducts the energy awareness program; and prepares annual energy reports in accordance with appropriate statutes.

The Base Energy Manager is located within the Asset Optimization Element which is a new capability in the recently reorganized Civil Engineer Squadron. The Base Energy Manager reports to the Asset Optimization Element Leader, who reports to the Asset Management Flight Chief, a new position that was created in the Civil Engineer Squadron reorganization.

As described in the Air Force Infrastructure Energy Strategy: "In most civil engineering squadrons today, energy management is a part-time job or an "additional duty," performed by an Energy Manager who is heavily tasked with non-energy activities, unable to focus on identifying real energy saving projects and potential investments."[172] Given the emphasis that is being placed on Energy Management throughout the Air Force, it does not appear that the Base Energy Manager is appropriately located within the installation organizational structure. Figure E-12 below demonstrates the layers of management through which a Base Energy Manager must report before having access to the Installation Wing Commander:

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172 Program Action Directive 07-02, 2007.

Figure E-12. Current Position of the Base Energy Manager.

As identified in Recommendation (1), the role of the Base Energy Manager should be expanded to include all installation energy management, and the location of the position within the installation organizational structure should be evaluated to determine if they are at a level that is commensurate with their responsibilities.

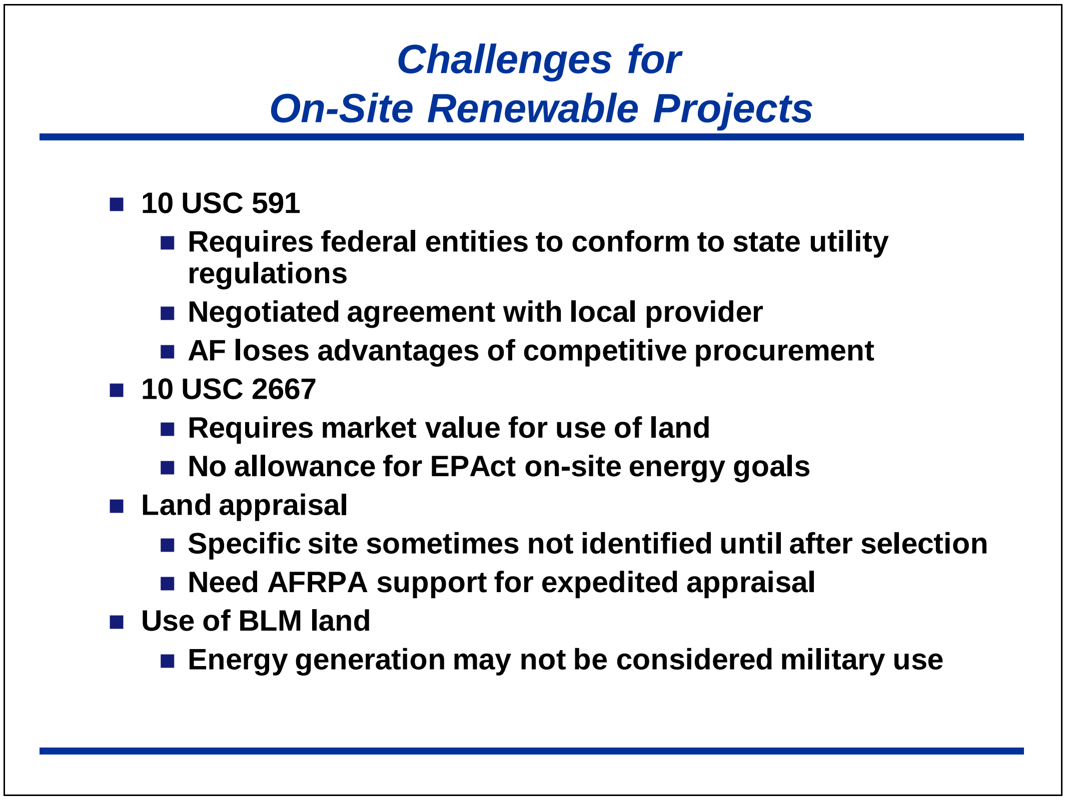

Figure E-13. Current Challenges for On-Site Renewable Projects.

The Federal Energy Management Program (FEMP) within the US Department of Energy's Office of Energy Efficiency and Renewable Energy published the Renewable Energy Requirement Guidance for EPACT 2005 and E.O. 13243 in January 2008. This document provides federal agencies with detailed guidance on: requirements for renewable energy from projects, purchases, and RECs to qualify as federal renewable energy consumption; on-site renewable energy projects; government-owned projects and distributed generation; purchases of renewable energy and RECs; REC retention requirements; and REC trading.

A Renewable Energy Playbook is under development at AFCESA. The first draft was developed in collaboration with the Air Force Real Property Agency and Air Force Center for Energy and the Environment. The playbook with be interactive and web-based and will identify:

- Roles and responsibilities,
- Governance and approval,
- Types of renewable energy for consideration,
- Feasibility of each type of renewable energy at an individual location,
- Available financing options, and
- The process to execute the renewable energy project.

The 35% draft was completed in April 2009, and a contract will be awarded for development of the final product.

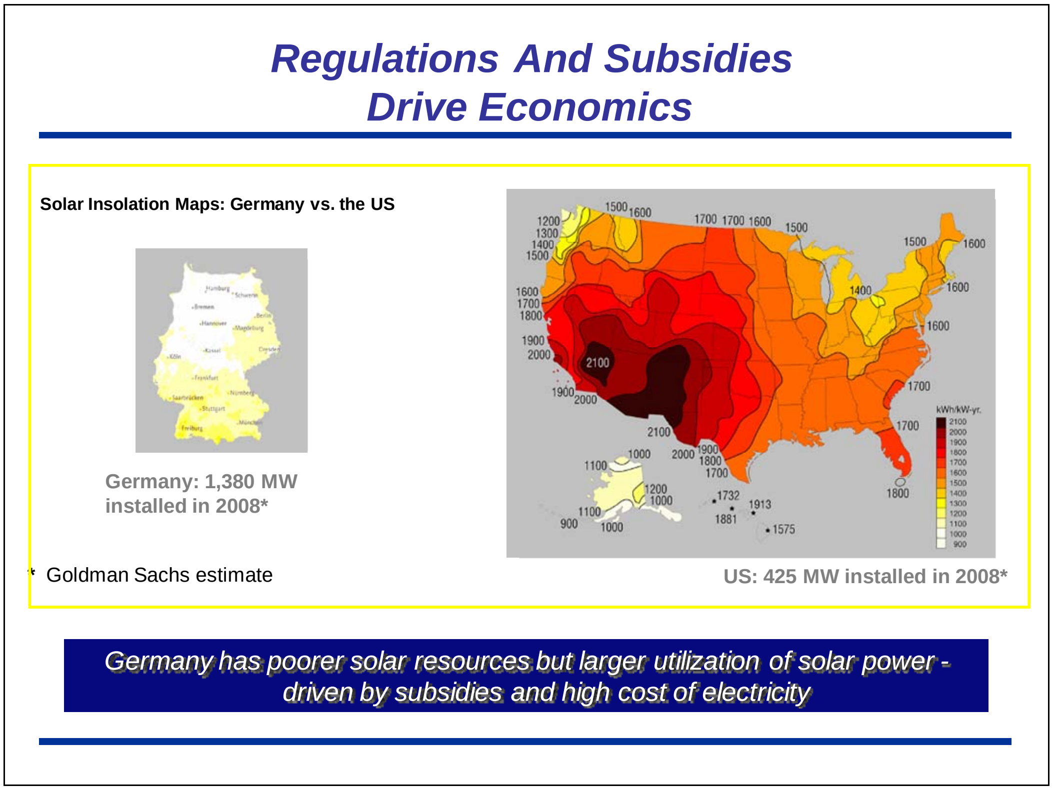

Figure E-14. Comparison of Solar Resources in the United States and Germany.

The increase in use of alternative energy sources varies in large part due to regulations and incentives provided by governing agencies. Policies that impact the speed of implementation of alternative energy technologies include:

- Feed-in tariffs which require power generators to purchase power from an alternative energy source at a higher than market rate,
- Government mandates and targets such as renewable energy portfolio requirements or minimum volumes of biofuels,
- Tax credits to encourage investment, such as production and investment tax credits;
- Tradable permits and other related market-based incentives, such as a carbon-based "cap and trade" system, which could increase the competitiveness of low-carbon alternatives;
- Carbon tax on carbon-based energy sources, and
- Loans, grants, subsidies and other support for alternative technologies, such as research and development support.

"Alternative Energy–Global Survey" was published by the Global Markets Institute of Goldman Sachs in the fall of 2007.[173] This study identifies the various alternative energy policies that have been established to promote the use of alternative energy in the United States, the European Union, Japan, Brazil, India, and China. The study found, for example, that

173 Global Markets Institute, 2007.

Germany's feed-in tariff system and additional subsidies have helped to make the country a leader in solar and wind power. As the report conclusion states:

> Energy policies put in place around the world during the last decade have helped the renewable energy industry to grow significantly. Because most renewable energy technologies are not yet, in most regions, able to compete economically with fossil fuels, they will have to be supported by public policy interventions if renewable energy is to play a real near term role in energy policy. Public policies are currently necessary to reduce the costs and improve the investment environment to enable significant and long-term growth in the use of renewable energy.

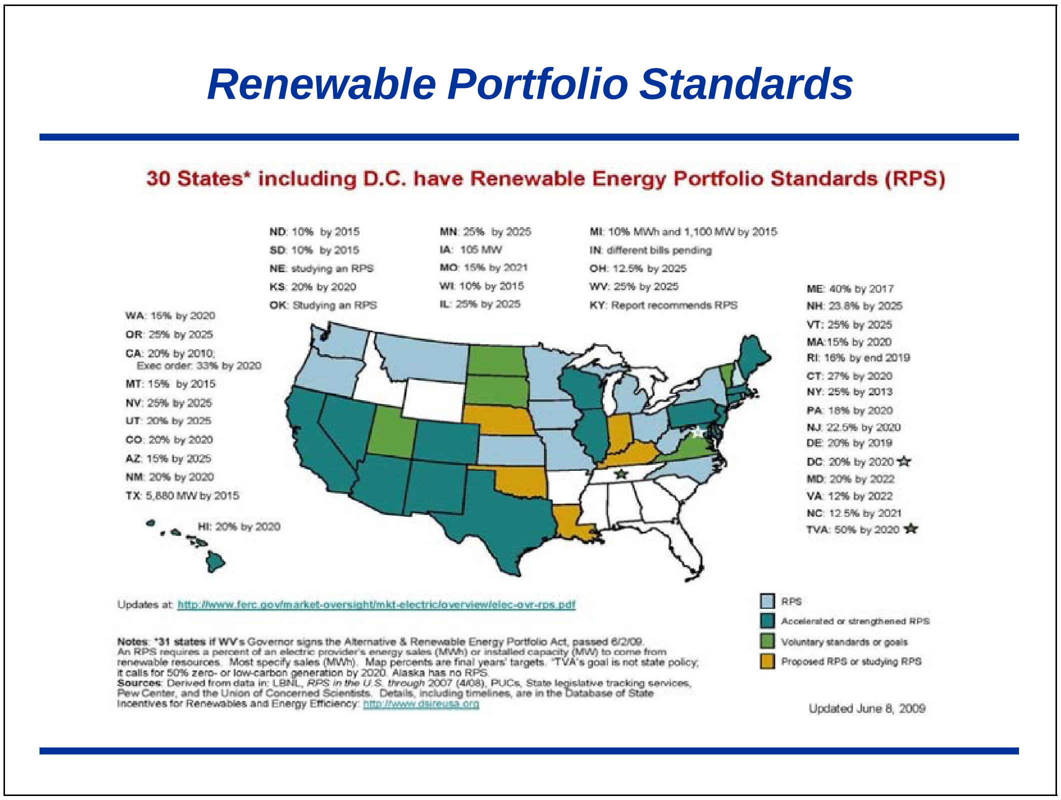

Figure E-15. States Utilizing Renewable Portfolio Standards.

Renewable Portfolio Standards typically require that a certain percentage of a utility's overall energy sales be derived from renewable sources. Most Renewable Portfolio Standards allow for flexibility of implementation by using tradable RECs, which are tradable certificates showing that one megawatt hour (MWh) of electricity has been generated by a renewable energy source.[174] RECs enable a utility to either generate its own renewable energy or buy credits from other suppliers. RECs, also called green tags, represent the technological and environmental attributes of generated power and give owners a green power credit of 1 MWh per REC.[175] Last year, RECs purchased by the Air Force accounted for approximately 8% of its electricity use.

174 *Ibid.*
175 Interstate Renewable Energy Council, 1998.

REC prices fluctuate based on supply and demand. AFCESA's Air Force Facility Energy Center in coordination with the major command energy managers, negotiates a better REC rate by making a consolidated annual purchase for the Air Force.

The Database of State Incentives for Renewables and Efficiency (DSIRE) is a comprehensive source of information on state, local, utility, and federal incentives and policies that promote renewable energy and energy efficiency.[176] DSIRE is an ongoing project of the NC Solar Center and the Interstate Renewable Energy Council funded by the Department of Energy. DSIRE is one of several resources that can be utilized to determine the best mix of renewable energy for a given installation.

The Air Force Facility Energy Center has been charged with implementing a centralized energy management approach and researching and identifying funding strategies and technologies that will assist the Air Force in meeting energy goals and mandates. The variation in policies and incentives by state and locality creates a challenge in developing a one-size-fits-all guidance document for base energy managers. Through investigating potential Enhanced Use Leasing options, the Air Force Real Property Agency partnered with the Department of Energy's Pacific Northwest National Laboratory to identify installations where on-site renewable development makes sense with respect to available resources (wind, biomass, geothermal, or solar), local renewable portfolio standards that provide economic incentives, and utility rates that support the economic viability of the envisioned project.[177] A partnership between the AF Facility Energy Center and the Department of Energy FEMP could be developed to create a resource to assist base energy managers in navigating the complex policies, regulations, and incentives that vary by state, yet help make alternative energy an affordable option.

Net metering (Figure E-16 below) is a policy that allows facility owners to receive the full value of the electricity that their alternative energy system produces. The term net metering refers to the method of accounting for an alternative energy system's electricity production. If more electricity is produced from the alternative energy system than the facility needs, the extra kilowatts are fed into the utility grid.[178]

Under federal law, utilities must allow independent power producers to be interconnected with the utility grid, and utilities must purchase any excess electricity they generate. Many states have gone beyond the minimum requirements of the federal law by allowing net metering for customers with alternative energy systems. With net metering, the customer's electric meter will run backward when the solar electric system produces more power than is needed to operate the home or business at that time. An approved, utility-grade inverter converts the direct current power from the photovoltaic modules into alternating current power that exactly matches the voltage and frequency of the electricity flowing in the utility line; the system must also meet the utility's safety and power-quality requirements. The excess electricity is then fed into the utility grid and sold to the utility at the retail rate.

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176 Database for State Incentives for Renewables and Efficiency, 1995.
177 Hood, 2008.
178 United States Department of Energy: Net Metering, 2006.

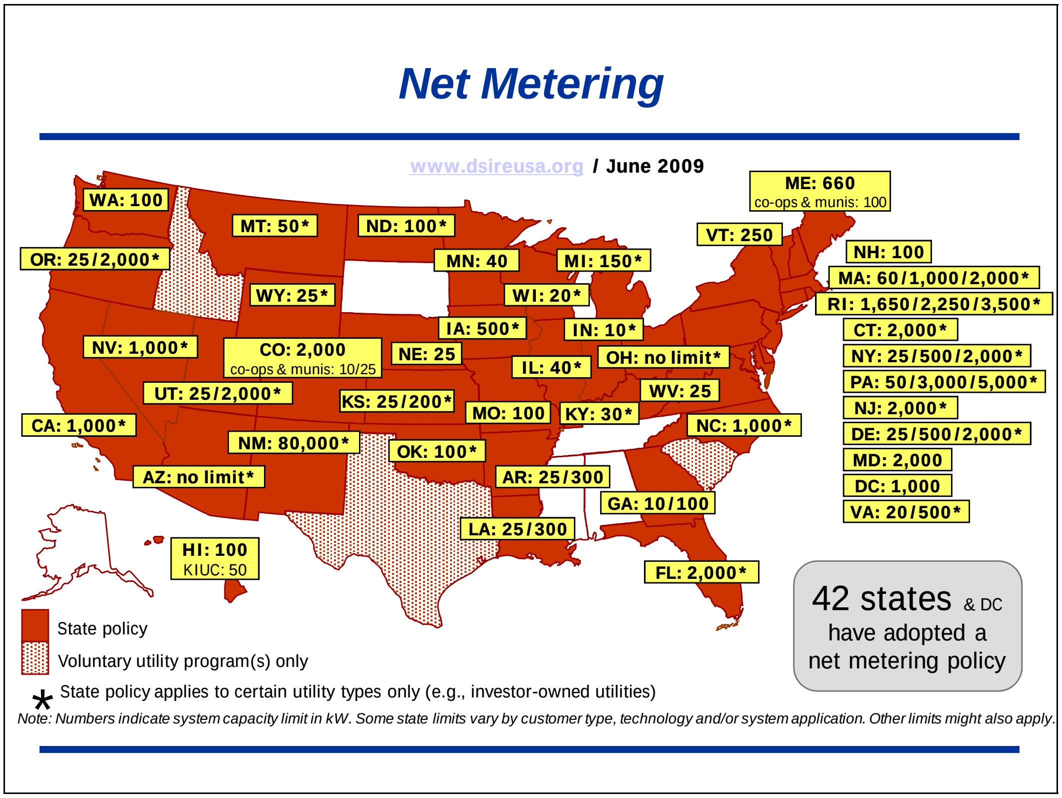

Figure E-16. States Utilizing a Net Metering Policy.

Net metering allows the customer to receive the full value of produced electricity without having to install a battery storage system. Essentially, the power grid acts as the customer's battery backup, which saves the customer the added expense of purchasing and maintaining a battery system.

The most important challenge of our age is to find a replacement for inexpensive fossil fuels–the energy sources that have fueled the industrial revolution, powered our military apparatus and form the economic basis of today's society. According to the Energy Information Administration, 88% of the world's energy needs are supplied by oil, coal, and natural gas (Figure E-17 below). According to the BP Statistical review of World Energy, in 2007 global primary energy consumption grew at 2.4% with coal remaining the fastest growing fuel. Two thirds of this growth globally is attributed to the Asian-Pacific region. Oil still leads the world in fuel usage, but has lost global market share for six consecutive years, while coal usage has grown for six years. Consumption of oil now takes place at the rate of one billion barrels every twelve days, but only 8 billion barrels are discovered yearly and the discovery trend is down.

World Reserves-to-Production ratios suggest that current oil, natural gas, and coal reserves will last about 40, 67, and 130 years respectively. This does not mean that the resources will disappear. It does mean that new and more costly reserves will need to be discovered and developed. The actual amount of fossil fuels that remain in the world is the sum total of (1) output from all of the world's producing reserves, which are in various stages of development, and (2) all the yet-to-be discovered reserves in their various states of development. Calculation of this value is further complicated, because of the variability and possible biases in publicly available data.

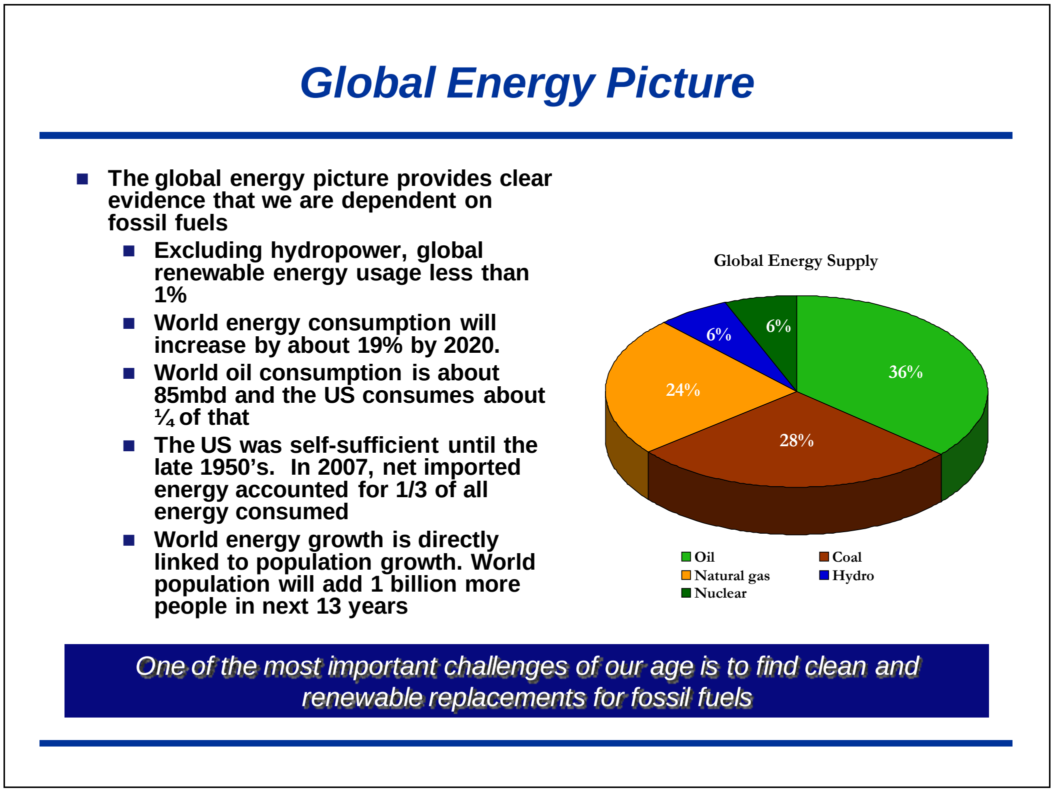

Figure E-17. Breakdown of Global Energy Consumption.

The Air Force is particularly dependent on fossil fuels for both its installations and its transportation needs. In fact, of all the fuel the Department of Defense uses each year, the Air Force accounts for more than half. During 2007 and 2008, record increases in world petroleum prices stoked renewed interest in finding ways to use renewable energy resources to displace energy derived from fossil fuels in both aircraft and at installations.

Appendix F: Previous Energy Studies

Summarizing the various prior studies, reports, and related documents relevant to the Air Force Scientific Advisory Board Alternative Energy for Airbases Study

F.1 Department of Defense Studies

DoD Energy Strategy, DSB Task Force Report, February 2008

The Defense Science Board (DSB) was tasked to find opportunities to reduce DoD's energy demand, identify institutional obstacles to their implementation, and assess commercial and security benefits to nation.

They identified two primary energy challenges: unnecessarily high and growing battle space fuel demands, and almost complete dependence of military installations on commercial power grid, leading to an unacceptably high risk of extended disruption of energy supply. They further found that their earlier recommendation from the 2001 DSB Task Force report was not implemented; that the DoD lacked the strategy, policy, metrics, information, and governance needed to manage energy risks, and that off-the-shelf technologies to make DoD more energy efficient were undervalued.

Their recommendations included accelerating efforts to implement the 2001 DSB Task Force recommendations, reducing risk at fixed installations due to power supply disruption, establishing a DoD-wide strategic plan and business process changes, investing in energy efficient and alternative energy technologies, and reducing energy use through policies and incentives.

Reducing DoD Fossil-Fuel Dependence, JASON Report, September 2006

JASON was tasked in 2006 by the Director of Defense Research & Engineering to assess pathways to reduce DoD's dependence on fossil fuels. The study covered following tasks: explore technology options to reduce the DoD dependence on fossil fuels and/or increase energy efficiency of our operating forces; assess the viability of technologies to provide at least the performance required of current DoD platforms and effort to integrate the technology and achieve the desired level of performance; assess blast and penetration resistance in lightweight vehicles; analyze structures and materials designs that could be adapted for use on combat and utility vehicles, or other DoD platforms; and to defer detailed analyses of USAF energy/fuel use.

The key conclusions and recommendation of the study were: consider buffers against future crude-oil and fuel price increases; make long-term planning for future fuel sources, production, and use; optimize exploitation of commercial aviation fuels; review and minimize CONUS fuel use; most DoD fuel is used in CONUS; track the pattern of use for vehicles and fuels; develop the necessary accounting and tracking tools to determine fuel delivery and logistics burdens and multipliers; determine fuel delivery/use logistics burdens and multipliers; lightweight armored and tactical vehicles, leveraging modern design, structural, and materials developments; and manned versus unmanned vehicles: reexamine and extend unmanned aerial vehicle, unmanned undersea vehicle, and robotic land vehicle uses.

Wind Farms and Radar, JASON Report, January 2008

JASON was asked by the Department of Homeland Security to review the current status of the interference that wind-turbine farms pose to air security radars within a ten-mile radius. They note that there is no fundamental physical reason why this interference should exist; rather, it stems primarily from the aging long-range radar infrastructure. The older technologies employed by many of these are poor at distinguishing wind farm signatures from airplanes or weather.

The report noted that mitigation measures may include modifications to wind farms, such as reducing radar cross section, and telemetry from wind farms to radar; modifications to radar, such as improvements in processing, design modifications, possible wholesale replacement, and the use of gap fillers in radar coverage; and regulatory changes in air traffic. The report noted that at the time of its writing, no funding was available to test how proposed mitigations would work in practice; and it proposed a government-industry partnership to find methods for funding studies.

F.2 Air Force Energy Studies

Technology Options for Improved Air Vehicle Fuel Efficiency, AF Scientific Advisory Board, May 2006

The SAB was tasked to explore potential scientific and technological solutions that could impact energy and fuel efficiency within the Air Force. The findings and recommendations on the alternate fuels are relevant to this study are quoted below:

"The study finds that the most promising of the potentially near term alternative fuels is liquid hydrocarbon fuels extracted from coal via Fischer-Tropsch processing."

"In the mid term, other hydrocarbon fuels, e.g., those extracted from shale or tar sands, or those synthesized from organic materials (biodiesel, ethanol, etc.) also show some promise, but less directly for aviation fuel replacements."

"If hydrogen ultimately can be produced such that there is a positive extractable energy balance, it does have promise in the mid-to-far term if used in fuel cells for auxiliary power units."

A Review of United States Air Force and Department of Defense Aerospace Propulsion Needs, AF Studies Board, National Research Council of the National Academy of Science, 2006

The National Research Council was requested to evaluate the United States aerospace propulsion technology base to determine if efforts under way will support necessary warfighter capabilities to 2020. The relevant recommendation from the study is:

"The Air Force should initiate a 5- to 7-year comprehensive program of fundamental fuels research. The goal of this program should be to study properties of smart fuel additives; surrogate fuels; synthetic fuel process technologies; synthetic fuels produced from feedstocks such as coal, oil shale, and biomass; and synthetic-conventional fuel blends. Systematic molecular and chemical kinetics modeling studies should be performed to establish a fundamental database of fuel and combustion properties."

Improving the Efficiency of Engines for Large Nonfighter Aircraft, AF Studies Board, National Research Council of the National Academy of Science, 2007

This study was requested to identify opportunities to address the impact of rapidly increasing aircraft fuel costs. The relevant recommendation from the study is:

"DoD should take steps beyond the B-52 flight demonstration to reaffirm its long-term commitment to synthetic fuels for its fleet of aircraft."

Producing Liquid Fuels from Coal, Prospects and Policy Issues, RAND Project Air Force, Dec 2008

The Rand study was conducted at the request of Air Force and the Department of Energy and examined the issues and options associated with establishing a commercial coal-to-liquids (CTL) industry within the United States. This report is very relevant to the current study and the key relevant principal findings of the Rand study are listed below:

"U.S. Coal Resources Can Support a Domestic Coal-to-Liquids Industry Far into the Future."

"Technology for Producing Coal-to-Liquids Fuels Has Advanced in Recent Years" and "Technology for Controlling Carbon Dioxide Emissions Is Advancing."

"A Combination of Coal and Biomass to Produce Liquid Fuels May Be a Preferred Solution" and "Developing a Coal-to-Liquids Industry in the United States Will Be Expensive, but Significant Production Is Possible by 2030."

"Coal-to-Liquids Development Offers Strategic National Benefits"

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Appendix G: Terms of Reference

USAF Scientific Advisory Board

Summer Study

FY 2009

Alternative Sources of Energy for US Air Force Bases

Terms of Reference

Background

US Air Force installations, both CONUS and OCONUS, are reliant on energy that is supplied via the local power grid. If the energy supply to these installations were disrupted, diminished, or denied, the operational and national security consequences could be considerable. Self-sustaining, alternative energy sources for AF installations could mitigate risks of power loss due to vulnerabilities in the local and national power grids and their aging infrastructure.

Study Products

Briefing to SAF/OS & AF/CC in July 2009. Publish report in December 2009.

Charter

This study will:

- Evaluate and assess current and projected Air Force installation energy needs, including consumption, conservation, and potential vulnerabilities to grid and other upsets. Consider both domestic and overseas bases, including expeditionary bases.
- Identify alternative energy sources for installations including energy generation and storage systems.
- Assess the potential benefits and challenges associated with identified alternatives. Explore the environmental, political, economic, and societal considerations in this assessment, as well as the ability for the base to operate independently of local power grids.
- Recommend potential energy technologies and systems that could be used for improved energy reliability, conservation, utilization, and independence for Air Force installations in the near-, mid-, and far-term.

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Appendix H: Study Members

SAB Members

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Appendix I: Study Meetings

USAF

HQ USAF Deputy Chief of Staff, Logistics, Installations, and Mission Support (AF/A4/A7)

HQ USAF Directorate of Operations (AF/A3O)

AF Civil Engineer Support Agency

Air Combat Command Director of Installations and Mission Support (ACC/A7)

AF Special Operations Command Directorate of Installations and Mssion Support (AFSOC/A7)

Air Force Research Laboratory

- Directed Energy Directorate (AFRL/RD)
- Materials and Manufacturing Directorate (AFRL/RX)
- Propulsion Directorate (AFRL/RZ)

United States Air Force Academy

1st Civil Engineering Squadron

99th Civil Engineering Squadron

99th Air Base Wing Public Partnerships Office

316th Civil Engineering Squadron

Other Agencies

National Security Space Office

Other Military Services

Office of the Assistant Secretary of the Army (Installations and Environment)

United States Army Nuclear and Combating Weapons of Mass Destruction Agency

Naval Facilities Engineering Command

Naval Sea Systems Command

Academia

California Institute of Technology

University of California, Los Angeles

Michigan Technological University

University of California, Berkeley

Missouri University of Science and Technology

Federally Funded Research Centers

Aerospace Corporation

Idaho National Laboratory

Los Alamos National Laboratory

National Renewable Energy Laboratory

Sandia National Laboratories

Industry

ARTEMIS Innovation

Electric Power Research Institute

MMA Renewable Ventures, LLC

NuScale Power, Incorporated

NV Energy, Incorporated

PNM Resources, Incorporated

Rolls-Royce Fuel Systems, Ltd

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Appendix J: Glossary

The terms and associated definitions used herein were derived from various sources and reflect the collective judgment of the SAB Panel as what would appropriately reflect the intended meaning of the term within the context of this Alternative Base Energy Study final report.

Air Turbidity – Haziness of air caused by individual particles.

Agro-Fuel – fuels which are derived from plant sources that have been deliberately mass-produced with the intention of creating bio-fuels.

Alkaline Fuel Cell – A well-developed and relatively efficient type of fuel cell technology that utilizes hydrogen and oxygen to produce water, electricity, and heat.

Alternative Energy – Energy from sources other than current primary sources intended to benefit national security, reduce foreign dependence on fossil fuels, and/or reduce global greenhouse gas emissions.

Amorphous – Refers to a lack of long range atomic lattice ordering in a solid (i.e., Amorphous Silicon, a semiconductor used in solar cells).

Amplitude – The maximum height of an ocean wave crest above water level.

Anaerobic Digestion – A proposed renewable energy technology in which microorganisms known as anaerobic bacteria are used to break down bio-degradable material in the absence of oxygen, producing biogas that can be used to generate electricity in heat. Anaerobic Digesters are dedicated airtight containers in which these processes take place.

Angstrom – A unit of length equal to 0.1 nanometer ($1x10^{-10}$ meter).

Anode – One of the two electrodes in an electrochemical cell or battery. The anode is the electrode at which oxidation occurs. For example, in a lithium ion battery undergoing discharge, it is the negative polarity electrode, where metallic lithium (in a lithium graphite composite) is converted into lithium ions and electrons are liberated to enter the circuit.

Array – A linked connection of modules such as array of solar modules (solar cells).

Atlas V – An expendable launch system in the Atlas rocket family that has been in use for NASA, Military, and commercial purposes since 2002. Military payloads have included communication, reconnaissance, and weather satellites.

Bathymetry – The study of the terrain of ocean or lake floors.

Battery – A device used to store electrical energy in the form of easily controlled electro-chemical reactions. During discharge, the stored chemical energy is converted to electricity.

Biofuels – Solid, liquid or gaseous fuels derived from biomass. A fuel must contain over 80 percent renewable materials in order to be considered biofuel.

Biomass – Biological material derived from living or recently living organisms including garbage, wood, waste, alcohol fuels, and landfill gas. Biomass is a renewable resource that can be used for fuels, power production, and products that would otherwise be made from fossil fuels.

Biomass Electric – The use of biomass to generate electric energy.

Biomass Thermal – The use of biomass to generate heat energy.

BTU – British Thermal Units are units of heat energy. One BTU is the amount of heat required to raise the temperature of one pound of water by one degree Fahrenheit. The unit MBTU refers to one thousand BTU, while the unit MMBTU refers to one million BTU.

CAES – Compressed Air Energy Storage is the process of using excess energy to compress air and storing it in an entity, such as an underground cavern, for later use in energy generation.

Capacity – The rate power output of a power plant (usually measure in megawatts or gigawatts).

Carbon Sequestration – Geo-engineered techniques used to capture and store carbon dioxide and other forms of carbon products.

Cathode – One of the two electrodes in an electrochemical cell or battery. The cathode is the electrode at which reduction occurs. For example, in a lithium ion battery undergoing discharge, the cathode is the positive polarity electrode made of lithium cobalt oxide ($LiCoO_2$), where electrons are consumed to drive lithium ions into the lithium cobalt oxide.

Circulating Power Fraction – The portion of the electricity used by a reactor itself.

CMMI – Capability Maturity Model Integration is a process improvement approach that provides organizations with the essential elements of effective processes. It can be used to guide process improvement across a project, a division, or an entire organization. CMMI helps integrate traditionally separate organizational functions, set process improvement goals and priorities, provide guidance for quality processes, and provide a point of reference for appraising current processes.

Cogeneration – Also called Combined Hear and Power (CHP). The process of using a device, such as a heat engine, to generate both energy and useful heat.

Cryogenically – Done at or having to do with very low temperatures.

Cyber – Having to do with electronic or computer-related environments; virtual.

Daylighting – The practice of using natural light to illuminate a room or building through the strategic placement of windows, skylights, and reflective surfaces.

Delta IV – An expendable launch system in the Atlas rocket family that has been in use for NASA, Military, and commercial purposes since 2002. Military payloads have included communication, reconnaissance, and weather satellites.

Fischer-Tropsch – Is a catalyzed chemical reaction in which carbon monoxide and hydrogen are converted into liquid hydrocarbons of various forms. Typical catalysts used are based on iron and cobalt. The principal purpose of this process is to produce a synthetic petroleum

substitute, typically from coal or natural gas, for use as synthetic lubrication oil or as synthetic fuel.

Effluent – Sewage or liquid waste.

Energy Savings Performance Contract – A funding mechanism that funds energy-saving upgrades using the savings from future utility bills, allowing federal agencies to obtain energy-efficient technologies without committing capital funds.

Energy Security – The integration of energy surety, survivability, supply, sufficiency, and sustainability.

Energy Sufficiency – Providing adequate power for critical missions.

Energy Surety – Preventing loss of access to power and fuel sources.

Energy Survivability – Ensuring resilience in energy systems to natural or man-made attacks.

Energy Sustainability – Promoting long-term support for the Air Force's mission, the community in which it is located, and the environment.

Electric Grid – The network of power transmission from the producer to consumer.

EO 13423 – "Strengthening Federal Environmental, Energy, and Transportation Management" is a Presidential Executive Order published in January 2009.

Feedstock – The plant or plant-derived raw material used to produce biofuels.

Flywheel – A mechanical device used to store rotational energy.

Flow Battery – A form of rechargeable battery in which a liquid electrolyte flows through an electrochemical cell that converts chemical energy to electricity. Because the active reactants are liquid, they can be stored external to the electrochemical cell, allowing scale up of power and capacity.

Fossil Fuels – Fuels generated from the decomposition of dead organisms. Common examples are oil, coal, and natural gas. These fuels are different from renewable energy sources in that they are not naturally or frequently replenished.

Furan – a colorless, volatile, heterocyclic organic compound obtained from wood oils and used in the synthesis of organic compounds.

Gasification – A process that converts carbon-based materials such as coal, petroleum, or biomass into carbon monoxide and oxygen, which can be used as fuel.

Generation IV Reactors – Theoretical nuclear reactor designs that are currently under research. These systems are expected to be cleaner, safer, more efficient, and more cost effective than systems currently in use.

Geothermal Heat Pump – A heating and/or cooling system that pumps heat from or to the shallow ground around it. It uses the relative stability of underground temperatures to make the system more efficient than typical air-source heat pumps. Also known as ground-source heat pumps or water-source heat pumps.

Grid – The infrastructure used to deliver electricity to the end user. It includes all components used to generate, transmit, control, and monitor electricity.

Halo – A concept in which a space based solar power system operates in a "halo" orbit around a point between the earth and sun.

Harden – The process of strengthening components or entire systems to protect them against natural or man-made destruction (normally associated with nuclear energy sources).

Heat Sink – An objects that absorbs or dissipates heat from another object.

High Temperature Electrolysis – A method of breaking down water into hydrogen and oxygen through the use of high temperature steam.

Hydrocarbons – Compounds composed exclusively of Hydrogen and Carbon atoms that facilitate combustion.

Hydrofoil – A wing-like structure mounted on the underside of a boat or vessel. When the vessel is traveling, the hydrofoil works to raise it out of the water to reduce drag.

Hydropower – Power produced by harnessing the force of moving water.

HMF – Hydroxymethylfurfural is a water soluble organic compound derived from dehydrated sugars that can be converted into a liquid biofuel.

Islanding – Electrical islands are created when parts of an interconnected power grid become separated from the main grid. This typically occurs during grid failures when portions of the area served are able to isolate themselves from the main grid and provide loads within that area, sufficient power from generation within the area, the "island." Islands can be created intentionally by establishing electrical boundaries using relays and controls that are able to isolate loads and sufficient generation to meet them, by ensuring loads and resources can be in balance.

ITER – The International Thermonuclear Experimental Reactor is an international project to design and build an experimental tokomak fusion reactor.

JASON – An independent scientific advisory group that provides consulting services to the US government on matters of defense science and technology. It was established in 1960. JASON typically performs most of its work during an annual summer study and has conducted studies under contract to the Department of Defense (frequently the Defense Advanced Research Projects Agency and the US Navy), the Department of Energy, the US Intelligence Community, and the Federal Bureau of Investigation. Approximately half of the resulting JASON reports are unclassified.

Jatropha Curcas – A hardy, pest- and drought-resistant species of flowering plant native to Central America. When the seeds of this plant are crushed, they produce both a high-quality biodiesel and a residue which can also be used as biomass feedstock or fertilizer.

Joule Program – A research development program within the European Commission focused on renewable energy and related fields.

Kobold System – A turbine system consisting of a rotor mounted on a vertical shaft which produces energy by exploiting marine currents.

Land Lease Agreement (LLA) – A contract between two parties where one party allows a second party to use its land in return for some type of compensation. The agreement between Tinker AFB and its local utility is an example. Here Tinker AFB allowed the

utility to install a gas turbine on its property in return for an upgraded electric grid and priority of the energy in the event of a grid outage.

Light Water Reactor – A reactor that utilizes "light water" (normal water) instead of "heavy water" which contains a heavier hydrogen isotope. Note: Lignin is a complex polymer, the chief noncarbohydrate constituent of wood, that binds to cellulose fibers and hardens and strengthens the cell.

Lignocellulosic Biomass – Biomass that is composed of cellulose and lignin, most commonly found in the woody cell walls of plant material.

Liquefaction – The process of converting a gas to a liquid.

Load – The amount of power required by the user.

Magnetized Target Fusion – a form of fusion power technology that combines principles from magnetic and inertial fusion technologies.

Mandates – Statutory requirement to meet an energy performance metric or standard such as the Department of Defense reducing its energy consumption by 30% by 2015.

Metal-Air Battery – A battery which produces electricity from the reaction of oxygen in the air with an oxidizable metal such as zinc or aluminum.

Microgrid – an aggregation of electrical loads and generation that can be controlled by a local energy management system.

Molten Carbonate Fuel Cell – A high-temperature fuel cell that contains an electrolyte composed of a molten carbonate salt mixture suspended in a chemically inert ceramic matrix.

Monocrystal – A homogeneous atomic alignment throughout a sample of a particular substance in a solid-state (i.e., monocrystalline silicon).

Multi Strand Sun Tower – A sun tower satellite system in which satellites are tethered to multiple "backbone" tethers to reduce the system's overall length.

National Ignition Facility – A a laser-based inertial confinement fusion research device located in Livermore, California. The facility uses lasers to heat and compress hydrogen fuel to the point where nuclear fusion reactions take place.

Net Zero – Refers to the capability of a facility (USAF Base in the present context) to generate as much energy as it uses, on an annual basis. Generally it is considered that the facility will generate this energy through various renewable or alternative energy systems located within the borders of the facility, although in some contexts the border can be extended (to the local community using facility assets, to Bureau of Land Management land, etc).

Net Zero Plus – The plus in net zero plus refers to the capability of a Net Zero facility (USAF Base in the present context) to provide additional power, typically to its surrounding community.

Network Single Point of Failure – A single network component that, if it fails, results in a nonfunctional service or network.

NHI – The Nuclear Hydrogen Initiative is a research and development program that aims to demonstrate the commercial-scale, economically feasible production of hydrogen using nuclear energy.

NREL – The National Renewable Energy Laboratory is a research and development laboratory focused on renewable energy and energy efficiency technologies.

Micro-grid – A local electric grid that can operate independently from the utility.

Off-Gassing – The evaporation or release of chemicals under normal conditions of temperature and pressure.

Osmotic Power – The energy retrieved from the diffusion of fresh water through a membrane into a salt water solution (osmosis) in order to equilibrate the salt concentration in the two fluids.

Osmotic Pressure – The pressure differential produced by osmosis.

Parabolic Trough – A type of solar thermal energy collector in which a long circular (paraboloid) mirror reflects and concentrates sunlight onto a vacuum tube.

Perpendicular to Orbit Plane – A space-based solar power concept in which a satellite is oriented so that throughout its orbit the solar collectors will face the sun and the energy transmitters will face the earth.

Petrochemicals – Chemical products made from raw materials of petroleum or other hydrocarbons that were once considered waste products. Petrochemicals are widely used in agriculture, in the manufacture of plastics, synthetic fibers, and explosives, and in the aircraft and automobile industries.

Pillars – Refers to the "Four Pillars of Facility Energy Strategy," developed by Air Force Civil Engineering as a facility energy strategy: 1) Improve Current Infrastructure; 2) Improve Future Infrastructure; 3) Expand Renewables; and 4) Manage Costs.

Phosphoric Acid Fuel Cell – A widely used fuel cell that uses liquid phosphoric acid as an electrolyte.

Photovoltaic Array – A linked assembly of photovoltaic modules.

Photovoltaic Cell – Often used synonymously with "solar cell," it is fundamentally based on the idea of the photoelectric effect to convert solar energy into electricity.

Polycrystal – Areas of uniform crystal structures that are discontinuous at various grain boundaries (areas separating single crystal states within a given sample).

Polymer Exchange Membrane Fuel Cell – A fuel cell that uses hydrogen as fuel and can operate at low temperatures.

Pongamia Pinnata – A drought-tolerant deciduous legume found throughout Asia. The seeds of this plant produce an oil that, with minimal processing, has been proven effective in running diesel engines.

Power Purchase Agreement – A contract between an electricity generator and a host site. An example is the agreement between Nellis AFB and a local energy company where Nellis provided the land for a solar photovoltaic farm in return for reduced energy prices.

Pressurized Water Reactor – A type of light water reactor in which water under high pressure transfers thermal energy to a steam generator.

PVWATTS – A system developed by NREL to calculate performance estimates nation-wide in grid-connected photovoltaic systems.

Pyrolysis – The thermal decomposition of organic material through the application of heat in the absence of oxygen. This process can be utilized to produce clean, high calorific gas from waste and biomass steams. Fast pyrolysis occurs in a time of a few seconds or less.

Radioisotopes – Any of the different types of atoms of an element that gained or lost one or more neutrons and are radioactive.

Rankine Cycle – a thermodynamic cycle which converts heat into work. This cycle generates about 80% of all electric power used throughout the world including most solar thermal, biomass, coal, and nuclear power plants.

Renewable Energy – Energy from sources which are naturally and frequently replenished.

Renewable Energy Credit – As defined in the United States, a tradeable certificate which represents proof to the Federal Government that 1 MWh of energy was generated by a renewable energy source.

Seagen – A large scale commercial tidal stream generator first implemented in 2008.

Simple Payback Period – A metric commonly used to evaluate energy-efficiency and sustainability investments, defined as the number of years it would take to recover a project's costs.

SMES – Superconducting Magnetic Energy Storage systems are short-duration systems which store energy in the magnetic field created by the flow of direct current in a superconducting coil which has been cooled to below its critical temperature.

Solar Ventilation Air Preheating – An energy saving technology that consists of a solar wall that amplifies, stores, and distributes thermal energy through a building.

Solar Thermal Steam – Steam produced by water heated with harnessed solar energy, which can be used for electric power production. This differs from photovoltaics, which convert solar power directly into energy.

Solar Water Heating – An energy saving technology in which solar energy is harnessed for its thermal energy to provide warm or hot water for residential or commercial use.

Solid Oxide Fuel Cell – A fuel cell which contains a solid oxide, or ceramic, electrolyte. These fuel cells have high efficiency, long term stability, and low emissions.

Stirling Engine – An engine in which work is performed by the expansion of a gas at high temperature to which heat is supplied through a wall. Like the internal combustion engine, a Stirling engine provides work by means of a cycle in which a piston compresses gas at a low temperature and allows it to expand at a high temperature.

Storage – The ability to capture excess energy and use it in future energy generation. Storage often involves converting energy from one form to another.

Substation – Part of an electric grid that transforms voltage of power provided from a generating source or another substation and then distributes it for local use.

Sun Tower – a space-based solar power concept consisting of a string of solar energy collecting satellites paired with a ground receiving unit.

Supervisory Control and Data Acquisition (SCADA) – Systems used in utility infrastructures as a computer-based monitoring and control system that centrally collects, displays, and stores information from remotely-located data collection transducers and sensors to support the control of equipment, devices, and automated functions.

Synfuels – Any liquid fuel obtained from coal, natural gas, or biomass. It can sometimes refer to fuels derived from other solids such as oil shale, tar sand, waste plastics, or from the fermentation of biomatter.

Synthesis Gas – A gas mixture with various amounts carbon monoxide and hydrogen that is often used as an intermediate product in the development of fuels such as synthetic natural gas.

Thermal Storage – An energy storage technology in which heat is stored in insulated repositories for later use providing heat or generating electricity.

Transmission – The bulk movement of electricity from power plants to distribution substations.

Thermal Storage – The capability for energy to be stored in a thermal reservoir, such as molten salt, where it can be used for future energy generation.

Tilt – A variation from the horizontal plane of a photovoltaic panel. The purpose of a tilt is to maximize the perpendicular components (maximize absorption) of incoming solar rays.

Tokamaks – A type of fusion reactor device that confines plasma in a toroidal (donut shaped) magnetic field.

Turbine Generators – A device than takes mechanical energy and converts it to electricity.

Venturi Pump – A pump with no moving parts that operates on the Venturi effect. The Venturi effect is the reduction of fluid pressure that results when a fluid flows through a constricted section of pipe. This reduction of pressure creates a vacuum which can be used to suck in another liquid or gas.

Very High Temperature Reactor – A theoretical nuclear reactor concept that functions at over 1000^{o} C.

Vitrification – The process of converting materials into a glass-like amorphous solid through a thermal process. When used to dispose of radioactive or hazardous waste, the hazardous particles are encapsulated and suspended within the leach-resistant glass matrix.

Waste to Energy – A form of energy recovery in which energy is created in the form of electricity or heat from the incineration or biological degradation of a waste source.

Watt – Standard unit of measurement for power representing 1 joule of energy per second.

Wavelength – The difference between the peak or crest of one ocean wave and the next.

ZEBRA – A high energy battery which uses molten salt as an electrolyte. The technical name for the battery is the $Na\text{-}NiCl_2$ (sodium-nickel chloride) and it is advertised as being zero-emission, non-combustible, and fully recyclable. Developed by and named after the Zeolite Battery Research Africa Project.

Appendix K: Acronyms and Abbreviations

#	Number
\$	United States Dollars
\$/P	Cost Per Unit Power
$\$_o$	Basic Cost
%	Percent
/	Divide, Per
~	Approximately
+	Add
$^+$	Positive Ion
−	Subtract
=	Equal To
>	Greater Than
÷	Divide
¢	Cents (In United States Dollars)
^{o}	Degrees
γ	Specific Heat Ratio
Δv	Change in Velocity
η	Efficiency
24/7	24 hours per day/7 days per week
24/7/365	24 hours per day/7 days per week/365 days per year
ABE	Alternative Base Energy
AC	Alternating Current
ACSIM	Assistant Chief of Staff for Installation Management
AD	Anaerobic Digestion
AEP	American Electric Power
AF	Air Force
AFB	Air Force Base
AFCEE	Air Force Center for Energy and the Environment
AFCESA	Air Force Civil Engineer Support Agency
AFI	Air Force Instruction
AFPD	Air Force Policy Directive
AFPM	Air Force Policy Memorandum
AFRL	Air Force Research Laboratory, Laboratories
AFRPA	Air Force Real Property Agency
AFS	Air Force Station
AFSOC	Air Force Smart Operations Command
AK	Alaska
aka	Also Known As
ARB	Air Reserve Base
ARRA	Americans for Responsible Recreational Access
ARS	Air Reserve Station
AS	Air Station

ASHRAE	American Society of Heating, Refrigeration, and Air-Conditioning Engineers
Aux	Auxiliary
ave	Average
AZ	Arizona
B	Billion, Billions
BEAR	Basic Expeditionary Airfield Resources
Bldg	Building
BOS	Basic Operating System
BTU	British Thermal Unit
C	Celsius, Circulating Power Fraction, Cost
C4ISR	Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance
CA	California
CAES	Compressed-Air Energy Storage
Capt	Captain
CCGT	Combined Cycle Gas Turbine
CE	Civil Engineering
CERL	Construction Engineering Research Laboratory
CERTS	Consortium for Electric Reliability Technology Solutions
CF	Capacity Factor
CFL	Compact Fluorescent Lights
CFR	Code of Federal Regulations
CFM	Cubic Feet per Minute
$(CH3)_2CO3$	Dimethyl Carbonate
$(CH_3)_2O$	Dimethyl Ether
CH_3OH	Methanol
CH_4	Methane
CHP	Combined Heat and Power
CIP	Critical Infrastructure Plan
cm	Centimeter
Cm^3	Centimeters-Cubed
CO	Carbon Monoxide, Colorado
CO_2	Carbon Dioxide
Col	Colonel
CONUS	Continental United States
CR5	Counter-Rotating Ring Receiver Reactor Recuperator
CRP	Conservation Reserve Program
CSP	Concentrating Solar Power
ct	Competing Technology
CT	Combustion Turbine
dBsm	Decibel Per Square Meter
DC	Direct Current
DDR&E	Director of Defense Research & Engineering
DE	Delaware
DoD	Department of Defense
DoE	Department of Energy

DSB	Defense Science Board
DSIRE	Database of State Incentives for Renewals and Efficiency
DSMES	Distributed Superconducting Magnetic Energy Storage
DUERS	Defense Utility Energy Reporting System
DWWT	Duckweed Based Wastewater Treatment
EfW	Energy From Waste
e.g.	For Example (*exempli gratia*)
EISA	Energy Independence & Security Act of 2007
EMS	Emergency Management System
EMSG	Energy Management Steering Groups
EO, E.O.	Executive Order
EPA	Environmental Protection Agency
EPAct	Energy Policy Act
EPRI	Electric Power Research Institute
Eqn, Eqns	Equation, Equations
ERDC	Engineer Research and Development Center
ESM	Energy Surety Micro-grid
exp	Exponential Function
F	Fahrenheit, Function
f_F	Structure Needed to Assemble System
FAA	Federal Aviation Administration
FEMP	Federal Energy Management Program
FFRDC	Federally Funded Research and Development Centers
FL	Florida
FLD	Field
FOB	Forward Operating Base
F-T	Fischer-Tropsch
ft2	Feet Squared
ft3	Feet Cubed
FY	Fiscal Year
G	Function, Geometric Factor
GA	Georgia
GE	General Electric, Germany
GIS	Geographical Information System
GS	General Schedule
GSHP	Ground Source Heat Pump
GW	Gigawatt
GWh	Gigawatt Hour
h	Hour
H_2	Hydrogen Gas
H_2O	Water
HI	Hawaii
HMF	Hydroxymethylfurfural
HVAC	Heating, Ventilation, and Air Conditioning
Hx	Heat Exchange
I	Solar Radiation
i.e.	That Is (*id est*)

IAP	International Airport
i-C_4H_{10}	Isobutane
ICE	Internal Combustion Engine
ID	Idaho
IEEE	Institute of Electrical and Electronics Engineers
IESNA	Illuminating Engineering Society of North America
IGCC	Integrated Gasification and Combined Cycle
IL	Illinois
IN	Indiana
IT	Italy
ITER	International Thermonuclear Experimental Reactor
JP	Jet Propellant, Japan
k	Page 133
keV	Kilo Electron Volts
K_g	Ground Station Efficiency Factor
kg	Kilogram
Kg/m^2	Kilograms per Meter-Squared
K_I	Inertial Confinement
k_L	Launch Mass Efficiency Factor
kLux	kilolux
K_m	Magnetic Confinement
km	Kilometer
KS	Kansas
kV	Kilovolt
kW	Kilowatt
kWh	Kilowatt-hour
L	Particle Density
LA	Louisiana
lbs	Pounds
LCC	Life-Cycle Cost
LED	Light-emitting diode
LEED	Leadership in Energy and Environmental Design
LFG	Landfill Gas
Li	Lithium
$LiCoO_2$	Lithium Cobalt Oxide
Li-ion	Lithium-Ion
LLC	Limited Liability Company
LMOP	Landfill Methane Outreach Program
LO	Low Observable
LPG	Liquefied Petroleum Gas
Lt Col	Lieutenant Colonel
Ltd.	Limited
LWRs	Light Water Reactors
m	Meter, Meters
M	Million
Mr	Mister
m/s	Meters per Second

MA	Massachusetts
MAJCOM	Major Command
Maj	Major
Maj Gen	Major General
MAP	Municipal Airport
max	Maximum
MBH	Thousand British Thermal Units per Hour
m_L	Cargo Mass Per Launch Vehicle
M_s	System Mass
M_{sc}	Mass of Supporting Systems
M_{TL}	Total Mass Launched
MBTU	Mega British Thermal Unit
MD	Maryland
ME	Maine
MEM	Microgrid Energy Management
MEP	Mobile Electric Power?
MGD	Millions of Gallons per Day
min	Minimum
MMBTU	Million British Thermal Units
MMcf	Million Cubic Feet
MN	Minnesota
MO	Missouri
MOGD	Methanol to Gasoline and Distillate
MPLS	Minneapolis
MSW	Municipal Solid Waste
MT	Mountain, Mount, Montana
MTG	Methanol to Gasoline
MTO	Methanol to Olefins
MTP	Methanol to Propylene
MW	Megawatt
MWe	Megawatts Electrical, Electrical Megawatts
MWh	Megawatt-hour
MWt	Megawatts Thermal, Thermal Megawatts
n	Particle Density
NA, N/A	Not Applicable
NAS	National Academy of Science
Na	Sodium
NaNiCl	Sodium Nickel Chloride
NaS	Sodium-Sulfur
NASA	National Aeronautics and Space Administration
NC	North Carolina
n.d.	No Date, Date Not Available
ND	North Dakota
NE	Nuclear Engineering, Nebraska
NECPA	National Energy Conservation Policy Act
NH	New Hampshire
NH_3	Ammonia

NHI	Nuclear Hydrogen Initiative
NiCd	Nickel-Cadmium
NIF	National Ignition Facility
NiMH	Nickel-Metal Hydride Cell
NIST	National Institute of Standards and Technology
NJ	New Jersey
NM	New Mexico
NMOC	Non-Methane Organic Compounds
NO_x	Nitrogen Oxides
NRC	Nuclear Regulatory Commission
NREL	National Renewable Energy Laboratory
NSSO	National Security Space Office
NW	Northwest
NV	Nevada
NY	New York
O_2	Oxygen Gas
O&M	Operation and Maintenance
OBT	Office of Building Technologies
OCONUS	Outside Continental United States
OH	Ohio
OK	Oklahoma
OMB	Office of Management and Budget
OSD	Office of the Secretary of Defense
out	Output
p	Power per Unit Mass, Particle Pressure
P	Total Power, Output Power
PA	Pennsylvania
PIWG	Provide Infrastructure Working Groups
POCC	Project Operations Control Center
PO	Portugal
P_p	Power Circulated to Particles
ppm	Parts Per Million
PSB	Polysulfide-Bromide
psi	Pounds per Square Inch
Pu	Plutonium
PV	Photovoltaic
PVC	Polyvinyl Chloride
pwf	Present Worth Factor
PWRs	Pressurized Water Reactors
Q	Relative Gain
R&D	Research and Development
RAF	Royal Air Force
RE	Renewable Energy
RECs	Renewable Energy Credits
Req’ts	Requirements
ROK	Republic of Korea
S	Sulfur, Power per Unit Area, Savings, Revenue

S2P	Sunshine to Petrol
S&T	Science and Technology
SAB	Scientific Advisory Board
SBSP	Space-Based Solar Power
SC	South Carolina
SCADA	Supervisory Control and Data Acquisition System
SD	South Dakota
SDHW	Solar Domestic Hot Water
SECAF	Secretary of the Air Force
SECDEF	Secretary of Defense
SEGS	Solar Energy Generation Systems
SERT	Solar Power Exploratory Research Technology
SES	Senior Executive Service
sec	Second
sf	Square Foot, Square Feet
SFG	Senior Focus Group
Si	Silicon
SMES	Superconducting Magnetic Energy Storage
SO_x	Sulfur Oxides
SP	Spain
sqmi	Square Mile, Square Miles
SSP	Space Based Solar Power
T	Temperature
t_d	Deploy Time, Time to Maintain Conditions
t_f	Finance Time
t_L	Launch Time
t_r	Characteristic Timescale
TiO2	Titanium Dioxide
TJ	Trillion Joules
TN	Tennessee
TOR	Terms of Reference
TRL	Technology Readiness Level
TU	Turkey
TV	Television
TW	Terawatts
TX	Texas
u	Exhaust Speed
U	Uranium
UPT	Undergraduate Pilot Training
UK	United Kingdom
US, U.S.	United States
USA	United States of America, United States Army
USAF	United States Air Force
USAFR	United States Air Force Reserve
USC	United States Code
USDA	United States Department of Agriculture
UT	Utah

VA	Virginia
VRB	Vanadium Redox Battery
vs., vs	Versus
VT	Vermont
w	Mass per Unit Area
W	Watt
W/kg	Watts per Kilogram
W/m^2	Watts per Meter-Squared
WA	Washington
Wh	Watt Hour
W_n	Nuclear Energy
W_p	Particle Energy
Wh	Watt-Hour
WI	Wisconsin
WEC	Wave Energy Converter
Wp	Watt Peak
WPD	Wind Power Density
WSHP	Water Source Heat Pump - chart
WtE	Waste to Energy
WV	West Virginia
WWTF	Waste Water Treatment Facilities
WY	Wyoming
x	Characteristic Dimension
yr, yrs	Year, Years
Z	Ion-Charge Number
ZEBRA	Zero Emission Battery Research Activities
ZnBr	Zinc Bromide

Appendix L: References

This reference list is intended to be a comprehensive list of the materials that informed the Panel members' deliberations during the course of this study. These represent the materials (briefings, papers, articles, etc.) made available to the members of the Air Force Scientific Advisory Board Alternative Base Energy Panel during the preparation for and conduct of the study. Many were provided by organizations/individuals that briefed the study and some were contributed by the Panel members themselves. In general these materials were provided as background information or as briefings during various fact finding trips undertaken by the Panel members. Many are not available for distribution beyond the Air Force Scientific Advisory Board as they contain classified, export controlled, proprietary, and/or For Official Use Only information. Any sources referenced/footnoted in the main body of this report represent a subset of this appendix.

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Appendix M: Initial Distribution

Air Force Leadership

SAF/OS – Secretary of the Air Force

AF/CC – Chief of Staff of the Air Force

SAF/US – Under Secretary of the Air Force

AF/CV – Vice Chief of Staff of the Air Force

Air Force Secretariat and Staff

SAF/AQ – Assistant Secretary (Acquisition)

SAF/CIO A6 – Chief, Warfighting Integration and Chief Information Officer

SAF/IE – Assistant Secretary of the Air Force for Installations, Environment, & Logistics

SAF/LL – Legislative Liaison

AF/CVA – Assistant Vice Chief of Staff

AF/RE – Chief of the Air Force Reserve

AF/SB – Military Director of the Scientific Advisory Board

AF/ST – Chief Scientist of the Air Force

AF/A2 – Deputy Chief of Staff, Intelligence, Surveillance, and Reconnaissance

AF/A3/5 – Deputy Chief of Staff, Air Space and Information Operations, Plans and Requirements

AF/A4/7 – Deputy Chief of Staff, Logistics, Installations, and Mission Support

AF/A7 – Director of Installations and Mission Support

AF/A8 – Deputy Chief of Staff, Strategic Plans and Programs

AF/A9 – Director of Studies and Analyses, Assessments, and Lessons Learned

AF/A10 – Assistant Chief of Staff, Strategic Deterrence and Nuclear Integration

NGB/CF – Chief of the Air National Guard

Air Force Major Commands

ACC – Air Combat Command

AETC – Air Education and Training Command

AFGSC – AF Global Strike Command

AFMC – AF Materiel Command

AFRC – AF Reserve Command

AFSPC – AF Space Command

AFSOC – AF Special Operations Command

AMC – Air Mobility Command

PACAF – Pacific Air Forces
USAFE – US Air Forces Europe

Combatant and Regional Commands
US Central Command
US European Command
US Joint Forces Command
US Northern Command
US Pacific Command
US Southern Command
US Special Operations Command
US Strategic Command
US Transportation Command

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Defense Policy Board
Defense Science Board
Naval Research Advisory Committee
Naval Studies Board

Executive Office of the President
National Security Council

Office of the Secretary of Defense and Defense Agencies
Under Secretary of Defense (Acquisition, Technology, and Logistics)
Deputy Under Secretary of Defense (Installations and Environments)
Director of Defense Research and Engineering
Defense Advanced Research Projects Agency

Department of Energy
Secretary of Energy
Under Secretary for Science
Under Secretary for Energy
DoE Federal Energy Management Program
DoE Energy Efficiency & Renewable Energy
Nuclear Energy Office
Office of Electric Delivery & Energy Reliability

Other Military Services

Assistant Secretary of the Army (Acquisition, Logistics, and Technology)
Assistant Secretary of the Army (Installations & Environment)
Assistant Secretary of the Navy (Installations & Environment)
Assistant Secretary of the Navy (Research, Development, and Acquisition)

Working Groups

Provide Infrastructure Working Group
All MAJCOM Civil Engineers and Energy Managers
Energy Senior Focus Working Group
Defense Energy Working Group
Interagency Energy Management Task Force

Joint Chiefs of Staff

Chair, Joint Chiefs of Staff
Vice Chair, Joint Chiefs of Staff
Joint Chiefs of Staff, Director of Intelligence (J-2)
Joint Chiefs of Staff, Director of Operations (J-3)
Joint Chiefs of Staff, Director of Logistics (J-4)
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ABSTRACT (Maximum 200 Words)

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The Study analyzed USAF installation energy needs and recommended alternative energy technologies, systems, and economic models that could satisfy the need for secure and reliable energy. The Study finds that the implementation of alternative energy requires a more concerted systems approach, including a cost/benefit tradeoff analysis for each installation. It recommends development of in-house competency and more effective utilization of expertise from DoE and others in areas of alternative energy implementation, microgrids, and systems security. For the mid- to far- term, the Study recommends the USAF partner with others in the development of technologies to create liquid fuels from renewable sources, as liquid fuels are crucial for aviation operations and of central importance to the USAF. The USAF should also partner with others on the adoption of clean and efficient backup power systems. Lastly, the Study finds nuclear energy could be an important element of secure energy at bases for which long-term grid outages are unacceptable. The USAF should evaluate the emerging small nuclear power systems and make nuclear energy a part of USAF energy planning for the future.

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